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DYNAMIC TESTING OF LARGE SPACE SYSTEMS

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16. ABSTRACT

Structural dynamicists are faced with basically an unsolvable problem: the prediction and verification of an analytical structural dynamic model to prescribed accuracy for use in control, loads, pogo, and aeroelastic design verification analysis. These verifications are accomplished through static and dynamic structural tests. This report deals with the subject of state-of-the-art dynamic testing, using as examples testing accomplished on the Space Shuttle and its elements. General conclusions on testing approaches are discussed, as well as future technology requirements.

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SECTION I. INTRODUCTION

Structural dynamicists are faced with basically an unsolvable problem the prediction and verification of an analytical structural dynamic model to a prescribed accuracy for use in control, loads, pogo, and aeroelastic design and verification analyses. Development of higher strength weight materials compounds this problem through lowering of frequencies. The accuracy of structural dynamic data required by these analyses is very stringent, leading to detailed structural modeling and testing. Under the present low-cost concepts, the dilemma is greatly increased since the very thing that reduces risk increases cost. In addition, a low-cost development program usually leads to an operations program that has risks and higher cost, which may not be acceptable. A survey of present and proposed space programs and problems in the transportation industry quickly identifies that not only are the accuracy requirements more stringent (Space Telescope), but the complexity of the dynamic system is greatly increased; unsymmetrical, jointed structures with many dynamic elements playing or "tuning" together (Large Space Structures). These systems must operate in severe, multifacet environments, from the high g space launch to the low g, long-term exo-atmosphere, necessitating consideration of large amplitude, nonlinear models which in many cases are designed by stiffness (deflection) requirements instead of strength. Often a multiplicity of higher ordered modes becomes significant. One additional complicating factor for modeling cannot be overlooked: the influence and coupling through joints, etc., of the overall or local dynamic characteristics with other subsystems or elements. Therefore, to minimize detrimental interactions, special consideration must be given to the following:

1) Engines
2) Pumps and rotating machinery
3) Control surfaces
4) Actuators
5) Control sensors
6) Engine/propulsion system support structure
7) Appendages
8) Liquid/structural coupling
9) Facilities (launch)
10) Joints

11) Trusses

12) Configuration buildup

13) Multiforce points

14) Nonlinear response analysis

15) Pointing systems

16) Time-varying structural characteristics.

The assumption that one can solve the accuracy problems of structural modeling through the use of testing is not the panacea that structural dynamicists dream of. Neither is the assumption that finer finite element grid models will produce more accurate analytical models. Test or analysis cannot totally duplicate the actual vehicle nor the expected flight environment. Models are just that – models. Therefore, the answer is a systems one. From the test side alone, the following questions arise:

1) How to take out test fixture constraints?

2) What are the actual boundary conditions?

3) How to simulate zero-g environments of large structures in a one-g environment?

4) What constitutes good data and correct modes?

5) How can you meet proper instrumentation requirements and data acquisition systems requirements?

6) How do you handle different scaling parameters in scale model testing (liquid versus structure, etc.)?

7) How does one account for the unpredictable phenomenon that always occurs (Saturn V Apollo local deflection in Instrument Unit)?

8) What tests are required?

9) What is the proper blend of analysis, test, and design requirements?

10) How does one extrapolate the data acquired to flight conditions?

The Shuttle Program made an attempt early to get a handle on these questions. A technology ad hoc committee was formed to study dynamic testing and related technology requirements. An industry/Government survey was conducted on dynamic analysis and testing, a symposium on substructure testing and synthesis was held, plus numerous meetings and after dinner discussions. Many ideas and much useful information were exchanged. This information is still of value to new programs and will be leaned on in this report. Special efforts during this activity were made by Thomas Modlin, JSC; Robert Goetz, LaRC, Summer Leadbetter, LaRC; Larry Kiefling, MSFC; Jack Nichols, MSFC; and experts in the aerospace industry. The purpose of this report will be to review the

Shuttle testing program and how it relates to these questions raised, drawing conclusions for testing and analysis in general. In addition, summaries of testing results from other programs and some future plans and technology issues will be presented.

SECTION II. SYSTEMS TRADES/TEST REQUIREMENTS

The static and dynamic behavior of space vehicles and spacecrafts during their different mission phases is a key consideration during design, development, and verification. How to most efficiently and accurately determine these structural characteristics is one key question facing not only the structural engineer but also the project and program offices. This question breaks down into several subquestions as follows:

1) Is analysis adequate without structural testing?

2) If testing is required, what testing is best, static influence coefficient, scale model, full scale elements, all-up full scale, or systems tests?

3) Are there design approaches, structural or control, passive or active, which if used would eliminate the requirements for testing?

In general, the answers to these questions are attacked at the single discipline level, structural dynamics. This is wrong. The structural dynamicist is a key player, but the total system and the related disciplines are fundamental parts. Thus, these questions can only be answered at the systems level and have different answers for each program or vehicle. Early in the program, system trades must be conducted which evaluate the options between interacting disciplines. Figure 1 depicts these key issues for the Space Shuttle vehicle [1-9].

For example, vehicle performance is a direct function of the structural weight. The structural weight can be reduced using load relief control logic; however, this requires turning the vehicle into the wind creating a non-optimum trajectory, performance wise. The inclusion of elastic body effects creates dynamic stability requirements which lead to reduced control gains that further reduce path deviations and structural weight savings. How accurately the bending dynamic characteristics can be predicted becomes a key factor in this trade. In addition, the control system complexity and reliability can be traded against the accuracy requirement placed on the bending dynamic characteristics. For example, an adaptive control system using state identification techniques can be used in lieu of stringent modal accuracy. Using stringent modal accuracy requirements allows the use of a simple, proportional gain control system with proven reliability and cost, while use of an adaptive system requires control system technology development and extensive verification test. Figure 2 illustrates the overall basic phenomenon as described. Figure 3 illustrates the flow of an adaptive system depicting the identification, decision, and adjustment flow.

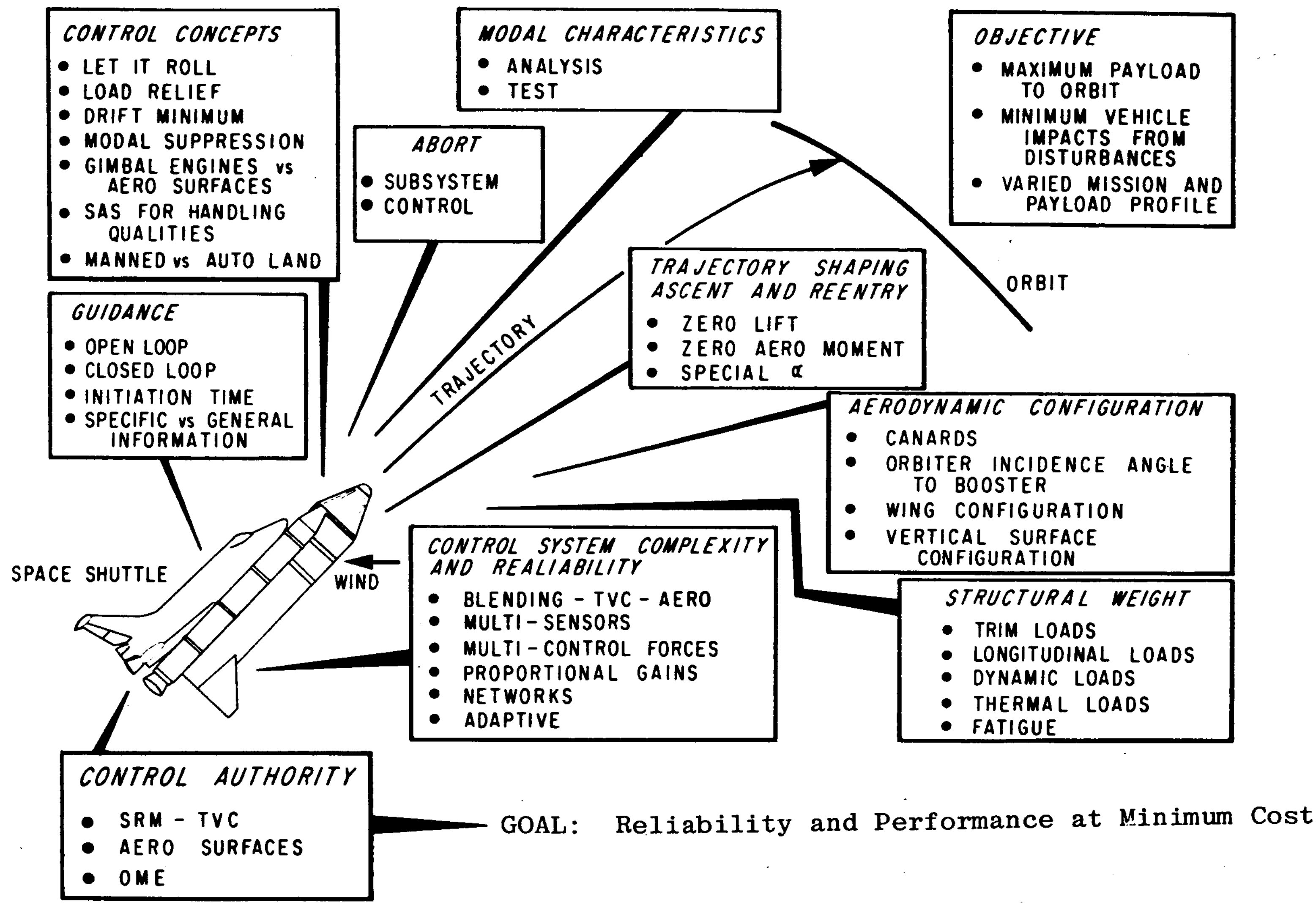


Figure 1. Key Shuttle issues.

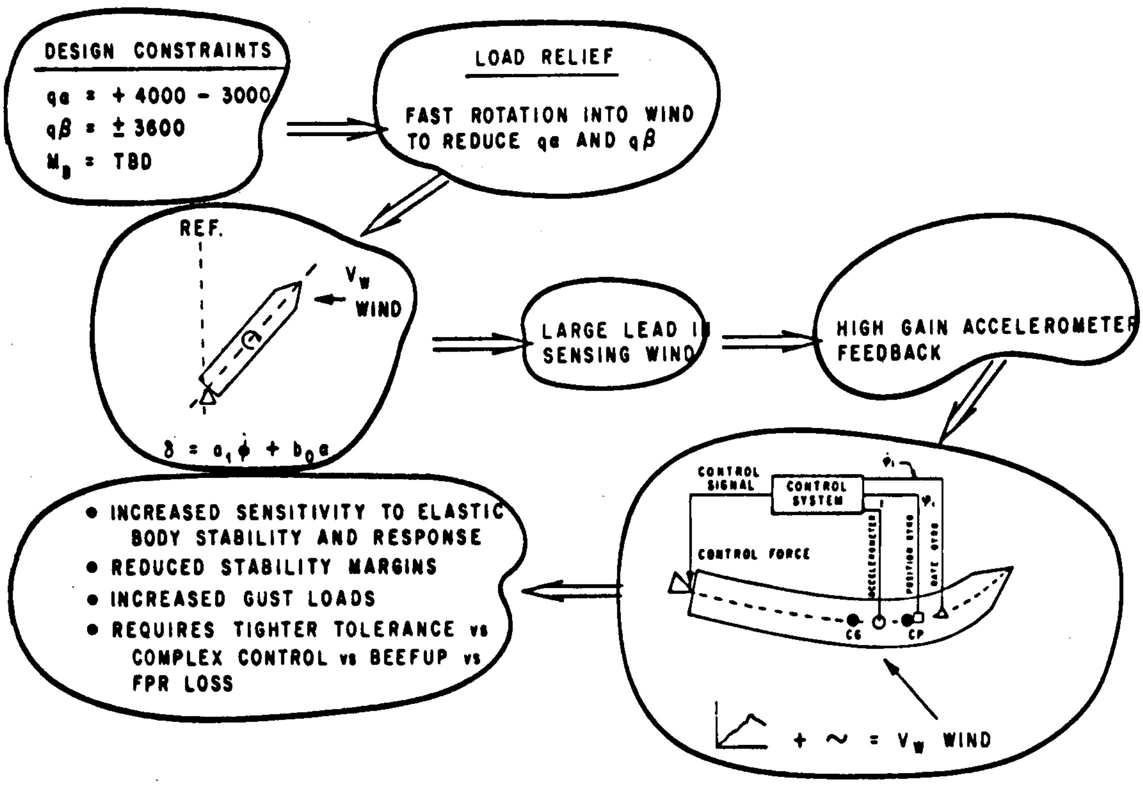


Figure 2. Control system logic modal accuracy trade.

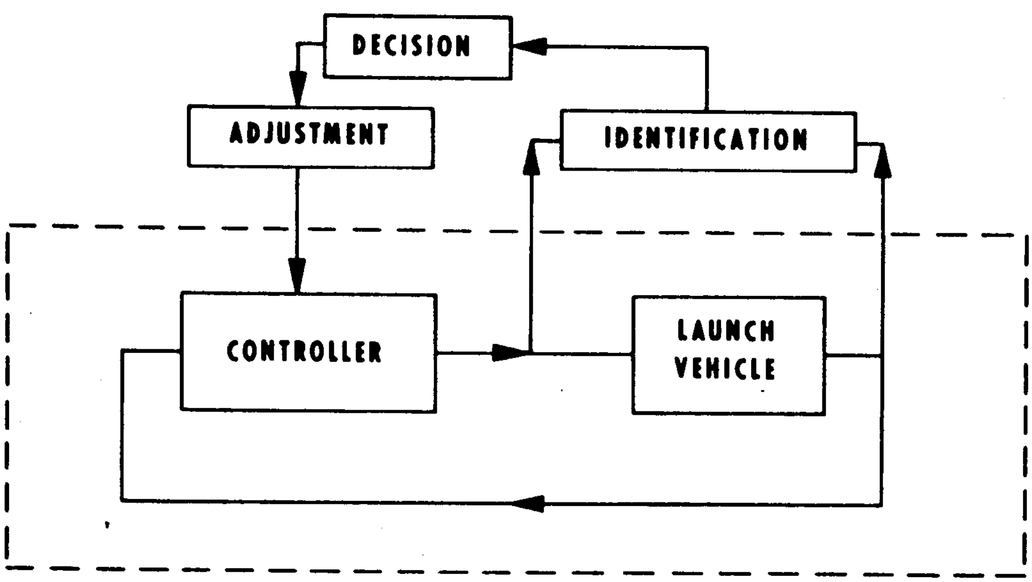


Figure 3. An adaptive system.

In order to properly arrive at these trades and requirements, a multidiscipline, interactive analysis is required. Figure 4 is a flow diagram for this type analysis for the Space Shuttle.

The environment, flight mechanics, configuration, induced environment, control system options, test options, propulsion and control effectors, and mission requirements must be simulated. In conducting these trade studies, the structural dynamicist must dig deep into his own area. Modal analysis is an important aspect of integrated analysis and program success and cost. The key issues here are the model details, choice of modeling elements, large number of degrees of freedom, and the accuracy requirements range. An integral part of this choice is static and dynamic test potentials which dictate the level of testing, components, boundary conditions, substructure, full scale, and scale model. Key technical issues in testing itself are facilities, suspension system, data validity, excitation system, evaluation, etc. Figure 5 illustrates these considerations [1].

For example, in the loads world, if the choice is made to design conservatively without static and dynamic tests, large uncertainty factors are used for design. Simplified models and conservative analysis approaches are possible choices. If the system is very sensitive and weight critical, low uncertainty factors, static and dynamic tests, and detailed analysis would be the choices.

Up to this point, the major illustrations have been structural control interaction effects as the driver to dynamic testing. The consideration must be broadened to include other disciplines where structural dynamic characteristics are important. These additional areas are loads, pogo, flutter, and other aeroelastic phenomena, such as acoustics. Figure 6 illustrates the various parts of the pogo loop [4,5,6].

Not only must the basic structural dynamic characteristics as entity be considered, but changes in these characteristics due to fluid coupling, acoustical coupling, and unsymmetrical vehicle coupling must be considered. This leads to a very complex set of requirements and costly analysis and test program considerations.

How all these requirements are brought together for a total program can best be illustrated using the Space Shuttle. The various disciplines working together arrived at a decision that the most reliable and cost-effective approach was through the use of a simple control system using proportional gains, time-consistent loads and accumulators for pogo suppression, in conjunction with a highly sophisticated analysis and test program. This approach has been chosen for every MSFC launch vehicle because of the control system availability and system response characteristics. For on-orbit programs (LSS), we have more choice in the control area because we have time (a slow-acting system). Figure 7 is a depiction of the question and the basic factors considered in arriving at this answer.

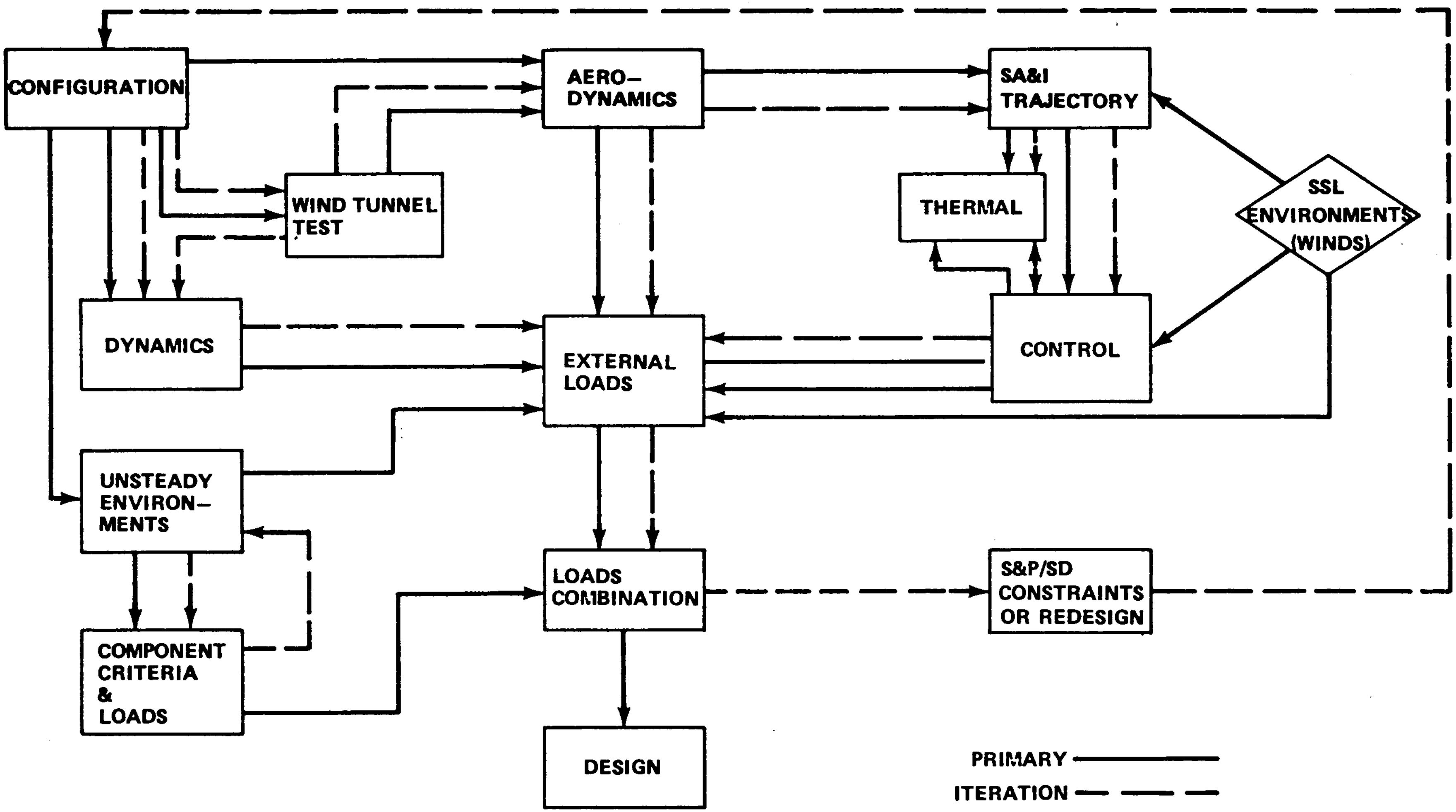


Figure 4. Systems Dynamics Laboratory environments and loads cycle.

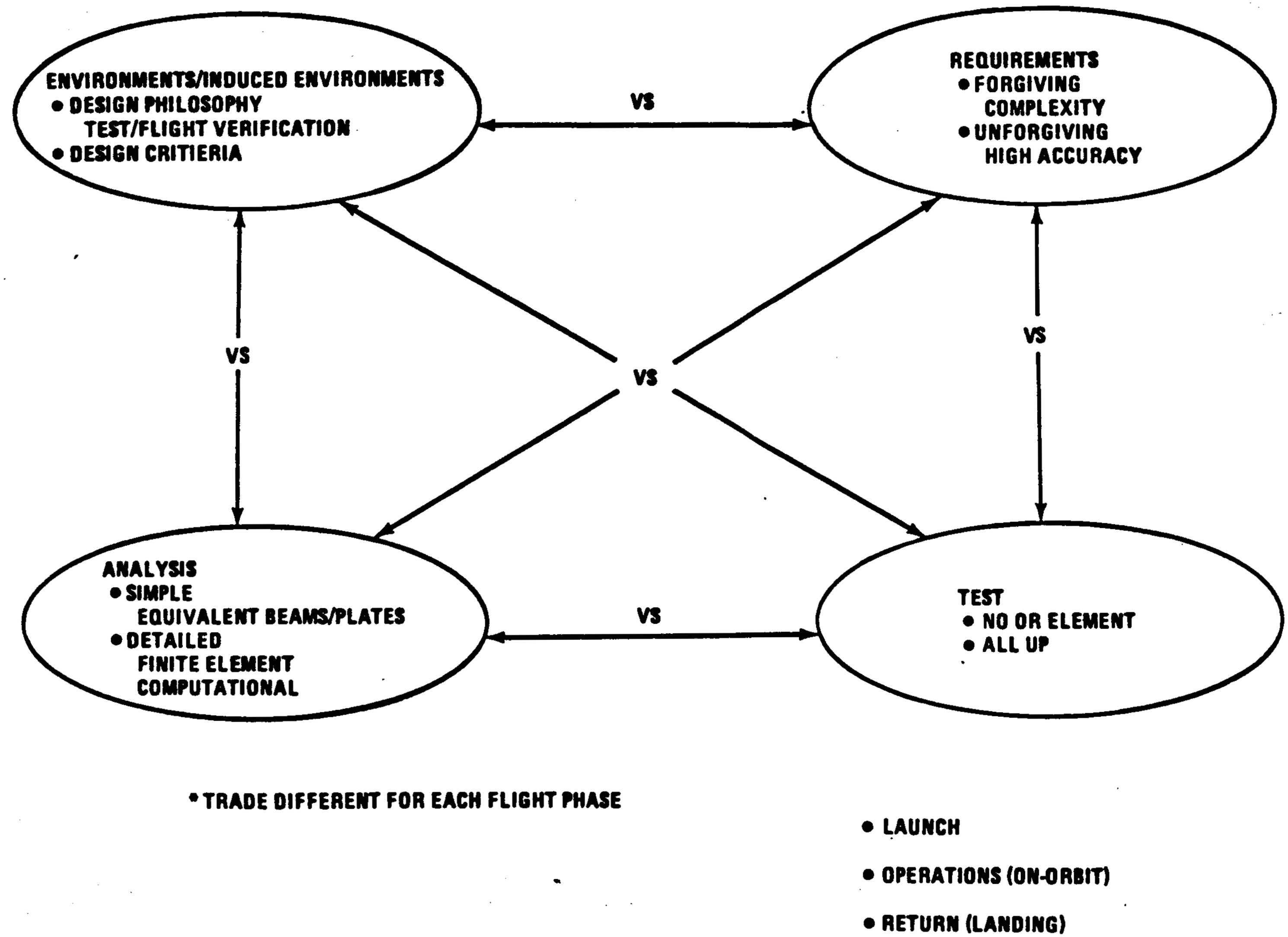


Figure 5. Structural dynamic trade studies.

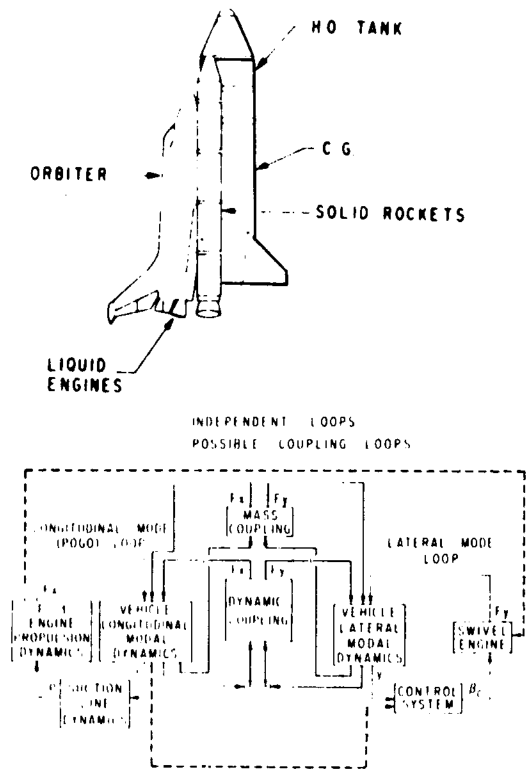


Figure 6. Block diagram of longitudinal and lateral system.

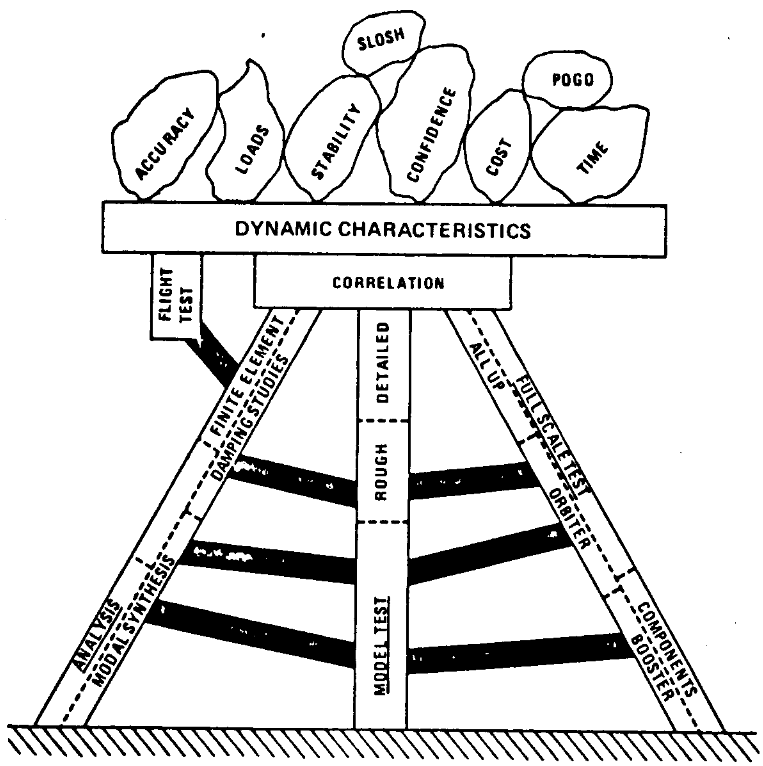


Figure 7. What is the best way to support the load?

As a result of this overall control system and test decision, the various analysis disciplines could develop a comprehensive set of modal accuracy requirements upon which to make the final choice of analysis and test approaches. Table 1 is a list of these accuracies arrived at for the disciplines, control, pogo, flutter, and loads.

TABLE 1. TEST REQUIREMENTS

ITEMS/USERS	CONTROL	POGO	FLUTTER	LOADS
FREQUENCY RANGE	0 – 10 Hz	0 – 50 Hz	0 – 40 Hz	0 – 20 Hz
FREQUENCY ACCURACY	5%<4Hz, 10%>4Hz	5%<3Hz, 15%>3Hz	5%	10%
DAMPING RANGE	> 0,005	~ 0.01	~ 0.01	~ 0.01
DAMPING ACCURACY	10%<4Hz, 20%>4Hz	20%	20%	20%
SLOPE ACCURACY	10%<4Hz, 20%>4Hz	N/A	15%	20%
DEFLECTION ACCURACY	10%<4Hz, 20%>4Hz	20%	15%	20%
PRESSURE ACCURACY		30%		

Notice that these are very high accuracy requirements on both frequency and modal deflection characteristics. In addition, the most elusive of all characteristics, structural damping, carries a minimum value for each discipline. At this point, implementation of the program starts. Actions required for this implementation are definition of the following:

1) Test facilities, fixtures, etc., design criteria
   a) Scaling laws
   b) Coupling between test article and facilities, fixtures
   c) Material properties
   d) Environments.
2) Excitation system
   a) Shaker size and location
   b) Control system.
3) Data acquisition
   a) Sensor choice
   b) Sensor location.

4) Data evaluation and analysis

   a) Accuracy

   b) Model update.

5) Pretest and model sensitivity analysis.

In summary, the question of whether to test or not and how to test is very complex. It starts with system trades and complexities and ends with how well the test can simulate the environments expected and produce verification data. Wedged in between are cost and schedule implications which many times are the deciding factors. Since this is written from the technical side, cost and schedules are not emphasized. Section III deals with the program arrived at for Space Shuttle, and Section IV discusses considerations for testing of large space systems. Section V deals with general technology requirements.

SECTION III. SPACE SHUTTLE TEST PROGRAM AND RESULTS

A. Overview

The Space Shuttle test program was under Johnson Space Center's (JSC) direction and, in general, implemented by Rockwell International Corporation. Marshall Space Flight Center (MSFC) was heavily involved, since they were responsible for the External Tank (ET), the Solid Rocket Boosters (SRB), and the Space Shuttle Main Engine (SSME) dynamic models and certain tests, such as lox modal survey and main ground vibration test. The opinions and viewpoints are those of the authors and are not necessarily held by all organizations and individuals involved; however, in general, they are the accepted corporate viewpoint arrived at through many meetings, telecons, and management reviews. The Shuttle configuration characteristics and accuracy requirements presented in Section II allows the identification of the key technical problems requiring resolution in the test verification program. These key technical problems are as follows:

1) Hydroelastic – unsymmetrical loading

2) Joints – local load paths – interfaces

3) Complex localized damping

4) Unsymmetrical coupling

   a) Dynamic

   b) Static

5) Viscoelastic coupling

6) Multimissions

7) Multipayloads

8) High modal density

9) Fast varying characteristics and environments

10) Reusability requirements

11) Complex structural, control, propulsion, and aeroelastic coupling

12) Stringent accuracy requirements

13) Extrapolation to test data to flight

14) Obtaining valid modes in test.

Those on this list that are in general, peculiar to the Space Shuttle are viscoelastic, many joints with local load paths and interfaces, unsymmetrical coupling static and dynamic, multimissions (lifetime), multiflight regime, and unsymmetrical hydroelastic loading. Not covered in this list are those peculiar to the engine system, which will be discussed later.

In order to solve these complex interacting dynamic problems, it was decided to use a building block and piggyback approach. Ideally, one would test each peculiar characteristic, such as viscoleastic, with small samples, move on, and test each subelement, element, all-up scale model, and then a full scale systems test. Ideally, the scale model would come early to identify generic problem areas. To a large extent, this was done for the Space Shuttle. During the technology days of Shuttle, a preliminary 1/8 scale configuration was built and tested by Langley Research Center (LaRC) to isolate generic coupling problems and determine basic characteristics requiring emphasis. This program was very successful and provided much information for the program and direction of the test program [10]. Since this was not the final configuration chosen for development, these results will not be discussed in detail; however, the references and bibliography are excellent reviews of this program.

As an outgrowth of this early program, basic design and system studies and reviews, a tentative test program was laid out. Figure 8 shows the general test categories, including piggyback tests and the results expected. Figure 9 is a matrix chart showing the test program elements and which technical problem will be emphasized in that test.

To determine the adequacy of the hydroelastic model, the full scale external lox tank modal survey is the prime source while the quarter scale ET element test would provide secondary data. By using the element approach here, the effects can be isolated and many conditions tested. Viscoelastic effects would primarily be determined using the coupon test with the quarter element test providing coupled verification. Local effects and unknowns could primarily be determined only in full scale due to quarter scale limitations, such as presence of instrumentation units and sensors. The same is true for load paths (joints and interfaces) due to manufacturing tolerance combined with gravity effects reducing accuracy in scale model testing. For example, if the manufacturing tolerances were the same in the quarter scale and full scale, the

- USE A BUILDING BLOCK TEST APPROACH WHICH TESTS MAJOR ELEMENTS SEPARATELY FIRST, THEN AS A SYSTEM.

TEST PROGRAM	GENERAL CHARACTERISTICS/PROBLEM IDENTIFICATION
o ONE-EIGHTH	
o LOX MODAL	HYDROELASTIC EFFECTS
o ORBITER HGVT	ORBITER CHARACTERISTICS
o QUARTER SCALE	EARLY DATA AND SUPPLEMENTARY DATA TO MVGVT
o SRM SEGMENT	DELETED FOR COST REDUCTION, SUBSTITUTED MORE COUPON TEST
o MVGVT	SYSTEM/INTERFACE DYNAMICS

- MAKE MAXIMUM USE OF OTHER TEST PROGRAMS TO OBTAIN SUBSYSTEM DYNAMIC CHARACTERISTICS

TEST PROGRAM	GENERAL CHARACTERISTICS/PROBLEM IDENTIFICATION
o MPT	ENGINE/THRUST FRAME/COUPLING POGO TRANSFER FUNCTION
o SRM DM'S	NOZZLE/ACTUATOR DYNAMICS
o CTL V	ACCUMULATOR CHARACTERISTICS
o SINGLE ENGINE DEVELOPMENT FIRINGS	POGO TRANSFER FUNCTIONS/ENGINE GAINS

Figure 8. General test approach.

REQUIREMENTS	STATIC AND COUPON	HGVT	QUARTER SCALE ELEMENT	QUARTER SCALE COUPLED	SSME MPT	LOX MODAL	MVGVT
HYDROELASTIC			S			P	
VISCOELASTIC	P		S				
DAMPING							P
LOCAL EFFECTS / UNKNOWNS							P
LOAD PATHS (JOINTS AND INTERFACES)	S			S			P
UNSYMMETRICAL DYNAMIC COUPLING				S			P
ACTUATOR/ENGINE/THRUST FRAME/LINE COUPLING					P		
SRB ELEMENT MODEL			P				S
SRB PRESSURE EFFECT	P		S	S			
ET MODEL			S			P	S
ORBITER MODE		P	S				S
EXTRPOLATION TO FLIGHT			S	S			P

NOTE: P = PRIME SOURCE; S = SECONDARY SOURCE

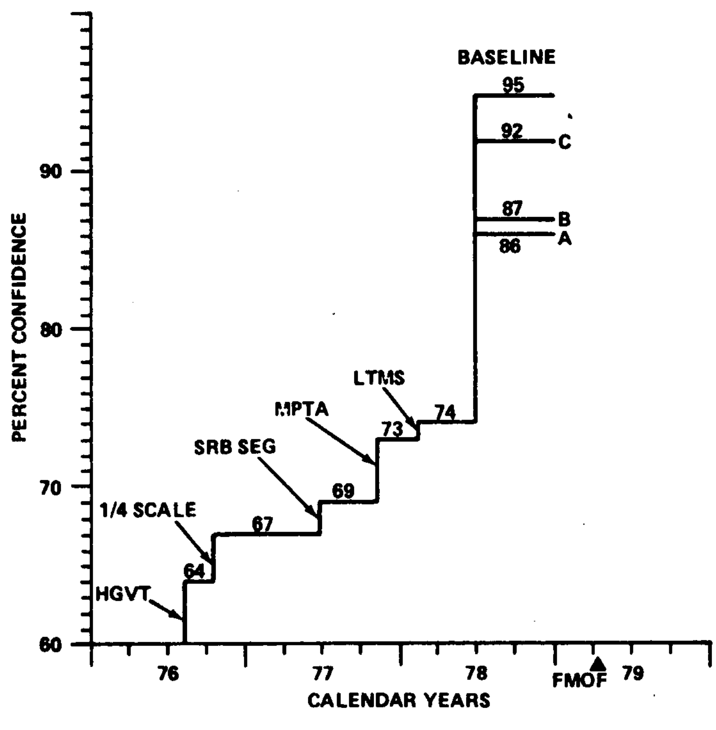
Figure 9. Technical requirements and test that satisfy requirements.

- o FABRICATION CONSTRAINTS LIMIT SCALING LOCAL STRUCTURAL FIDELITY.
  - THIN SKIN WELDING TO RING FRAME MASS CAUSES LOCALIZED BULKING, DEGRADING LOCALIZED RESPONSE.
  - ET QUARTER SCALE LOX TANK OGIVE WELD LANDS INCREASED LOCALIZED SHELL FREQUENCIES 3 TO 15 PERCENT AND SECOND BENDING BY 8 PERCENT.
- o QUARTER SCALE LOCAL RESPONSE CANNOT BE AS ACCURATE AS FULL SCALE DUE TO SIMULATION VERSUS REPLICATION OF:
  - CREW CABIN.
  - CONTROL SURFACE ACTUATORS.
- o SCALING PROBLEMS DEGRADE EXTRAPOLATION TO FLIGHT VEHICLE MODEL.
- o ANOMALIES ARE LIMITED TO THE DEGREE OF MODEL REPLICATION.
- o MANUFACTURING TOLERANCES SAME AS FULL SCALE.
  - JOINT FIDELITY.
  - FORCE TO RESPONSE SCALING (FORCE LEVEL TO RESPONSE LEVEL).

Figure 10. Quarter scale limitations.

quater scale would be the equivalent of testing full scale at 1/4 of g, thus opening up joints. The structural frequency scales are inversely proportional to the geometric scale factor and slosh frequency scales are inversely proportional to the square root of the geometric factor; therefore, fluid structural interactions are not properly related to subscale models Figure 10 lists quarter scale model testing and considerations. The quarter scale model manufacturing tolerances were changed to eliminate part of this problem and was successful in this light.

Unsymmetrical coupling would mainly be verified on the Mated Vertical Ground Vibration Test (MVGVT) for the same reasons given above; however, quarter scale would provide significant information. Actuator/engine/thrust frame/line coupling can only be verified on MPT due to hardware limitations on MVGVT. The SRB model is verified in the quarter scale element and special coupon test. The Orbiter model is verified in the Horizontal Ground Vibration Test (HGVT) with the extrapolation to flight conditions done using MVGVT. As a means of arriving at these conclusions and assessing the confidence level of the model accuracy being met in the test program, a progressive confidence level assessment was made for the test program. Figure 11 is the results for the control system requirements.



A	B	C
ET/SRB	ET/SRB/DO	ET/SRB/DO
HVGVT (2)	ET/DO	ET/DO
SEN. STUDY	HVGVT (2)	ET/SRB/101 ORB (1 COND.)
	SEN. STUDY	SEN. STUDY

Figure 11. Confidence factor versus test combination (control).

Although accurate, quantitative levels cannot be produced, these levels show the relative risks between the different tests. The total test program is required to meet the 95 percent confidence required for launch. A different blend is obtained when making the same assessment for pogo (Fig. 12). The basic conclusion is the same driving the all-up test requirements.

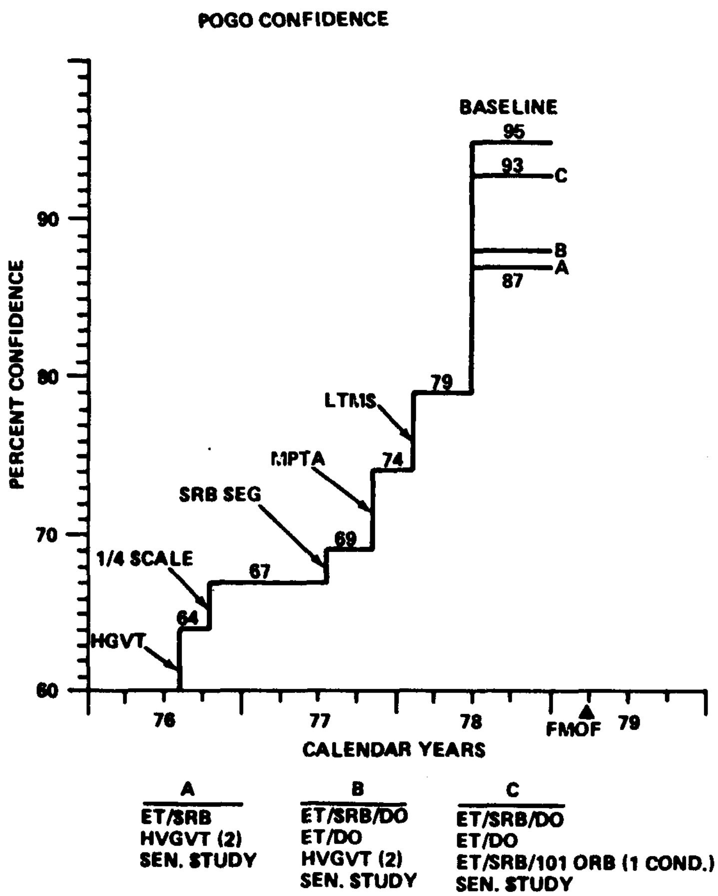


Figure 12. Confidence factor versus test combination (pogo).

Once the system baselined this program, the next step was of a fourfold nature: (1) insuring that the hardware had adequate fidelity to achieve the test objective, (2) designed and verified facilities and suspension systems to insure proper boundary conditions and meeting test objectives, (3) development of the excitation and acquisition system, and (4) management and control techniques for handling test, data exchange, models, etc. Obviously, a strict discussion of these areas is presented with the discussion for each test. An example of how these areas are driven is the control engineer's desire not only to get modal data accuracy requirements met, but to get empirical transfer functions between the control force applications points and the various control force sensors. This drives a complete set of control sensors, shaker application points at the gimbal, and accurate boundary conditions. The other question relating to data acquisition, excitation, and evaluation is discussed under each individual test.

As a means of insuring that these activities are handled properly, Level II instituted several activities. An overall test plan was developed that included technical requirements as well as management operations and test readiness reviews [11]. Figure 13 shows the TRSD change control.

The loads panel functioned in technical requirements, models, etc. In addition, an MVGVT Requirements Board was formed to integrate all discipline requirements and verify that they were met. A test board was set up to control changes and their implementation. The normal level controls and reviews also used such groups as the Systems Integration Review (SIR), Ascent Flight Systems Integration Group (AFSIG), and Program Review Change Board (PRCB).

B. Mated Vertical Ground Vibration Test

The MVGVT consisted of two basic configurations — launch and boost. The launch configuration was composed of two SRB's, an ET, and an Orbiter (OV-101). For the launch configuration, the liftoff and end burn (pre-SRB separation) flight conditions were tested. The liftoff testing began on October 20, 1978, and ended December 2, 1978. The end burn testing started on January 30, 1979, and ended February 28, 1979.

The boost configuration was composed of the ET and the Orbiter (OV-101). For the boost configuration, three flight conditions (start boost, mid-boost, and end boost) were tested. The boost test started on May 30, 1978, and ended July 14, 1978.

The MVGVT provided an experimental data base in the form of structural dynamic characteristics for the Shuttle vehicle. This data base was used in developing high confidence analytical modes for the prediction and design of loads, pogo, controls, and flutter for the Space Shuttle under various payloads and operational missions.

The test article was subjected to sinusoidal excitation by driving shakers selected and located so as to excite and isolate all significant modes of vibration, both symmetrical and antisymmetrical. The frequency range of interest that was surveyed is as follows:

1) For transverse excitation, 1.5 to 30.0 Hz

2) For longitudinal excitation, 1.5 to 50.0 Hz.

The test objectives of the Shuttle vehicle MVGVT were as follows [12]:

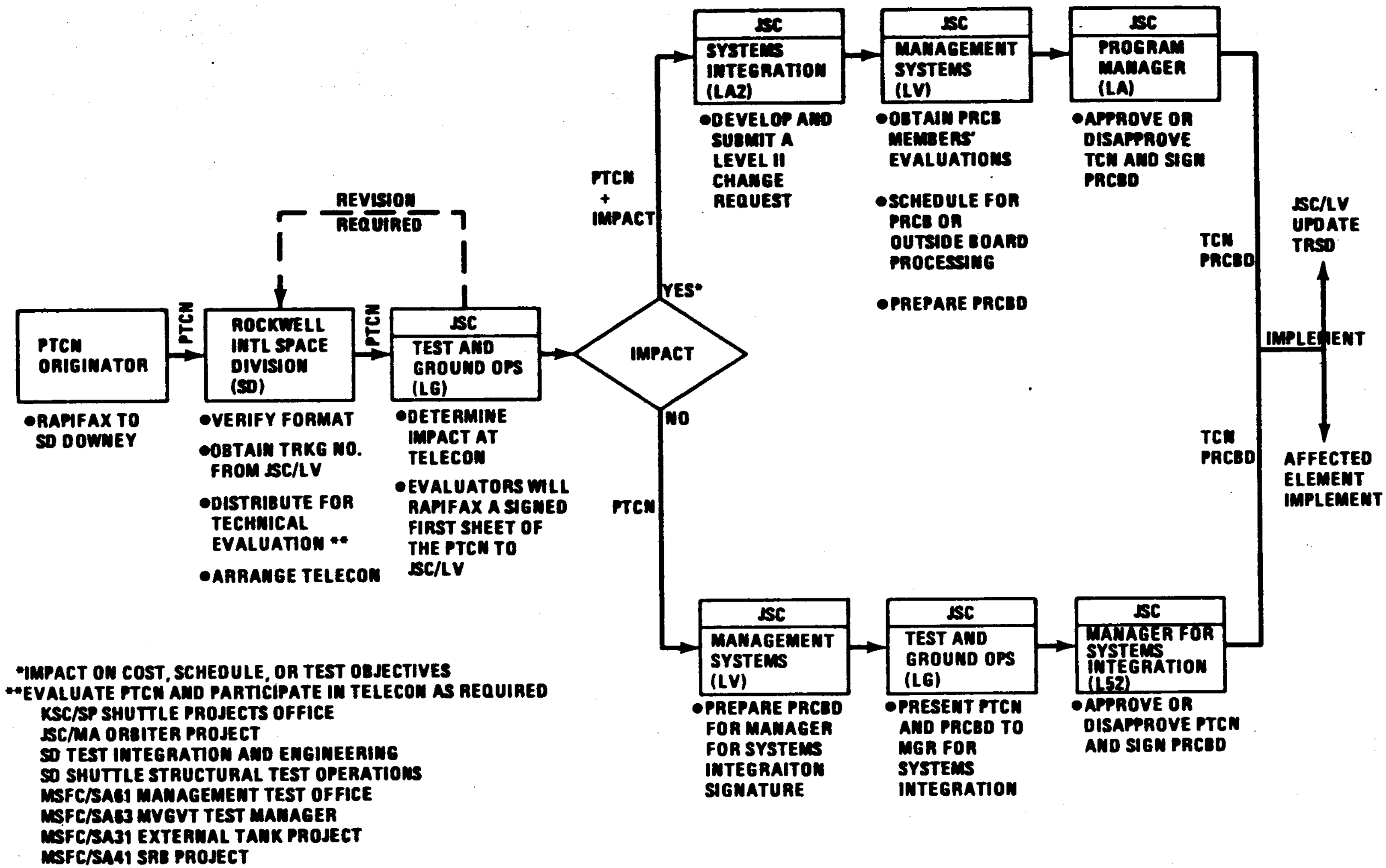


Figure 13. MVGVT TRSD change control.

1) To verify the coupled dynamic math models of the mated Shuttle configurations through correlation of analytical predictions to measured test data. These data shall consist of mated structural resonant frequencies, mode shapes, and damping characteristics for selected simulated flight conditions.

2) To obtain experimentally the modal translations and rotations at the Orbiter and SRB guidance sensor and effector locations for the mated Orbiter/ET and Orbiter/ET/SRB configurations.

3) To obtain experimentally the test transfer functions from the excitation sources to the guidance and control sensor locations for the mated configurations.

4) To measure ET umbilical feedline modal data to verify the feedline math model.

A listing of the accuracy requirements for the Shuttle dynamic modal data as specified by the users, namely controls, pogo, flutter, and loads by discipline in Table 1.

The liftoff and pre-SRB separation test configuration utilized a soft suspension system that was provided by the four existing Saturn V pneumatic/hydraulic units. The hydraulics provided the vertical support and six degrees of freedom for the supported vehicle. The test configuration is shown in Figure 14. Each SRB aft skirt was attached to an adapter truss, which rested on the hydraulic system. The lateral stability and soft spring rate in pitch and yaw were provided by Firestone airbags.

The three boost configurations suspension system consisted of two pyramid-shaped truss airbag assemblies. Each assembly was composed of 12 airbags with reservoirs, a rod tension member, spreader beam cable assembly, and an ET spreader beam, which connected to the test article at the forward ET/SRB attachment. For pitch and yaw stability, upper and lower Firestone airbags were used. The boost test configuration and suspension system is depicted in Figure 15.

A typical RGA response to pitch excitation is shown in Figure 16. The response is due to four SRB and two Orbiter shakers operating simultaneously over a 2 to 15 Hz frequency range. A typical modal vector plot for the pitch plane of acceleration is shown in Figure 17. The liftoff symmetric test frequencies versus pretest analysis are presented in Table 2 and are typical results. The modal damping calculated from the decay trace and modal descriptions for each is also shown.

The launch and boost modal survey tests were successfully completed and met all the requirements and objectives. A summary of the most significant results derived from the MVGVT program is as follows:

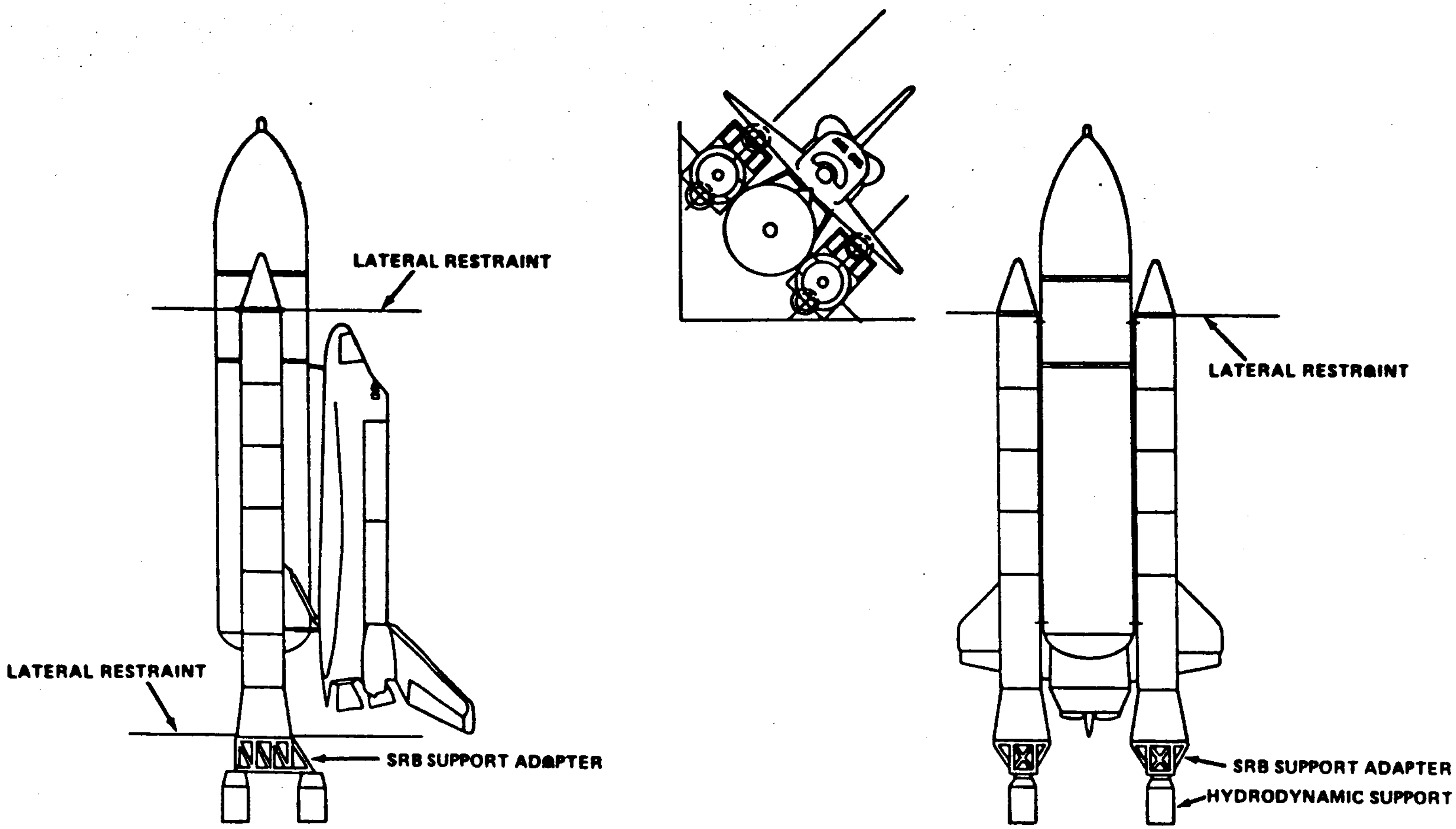


Figure 14. Suspension system for Shuttle vehicle.

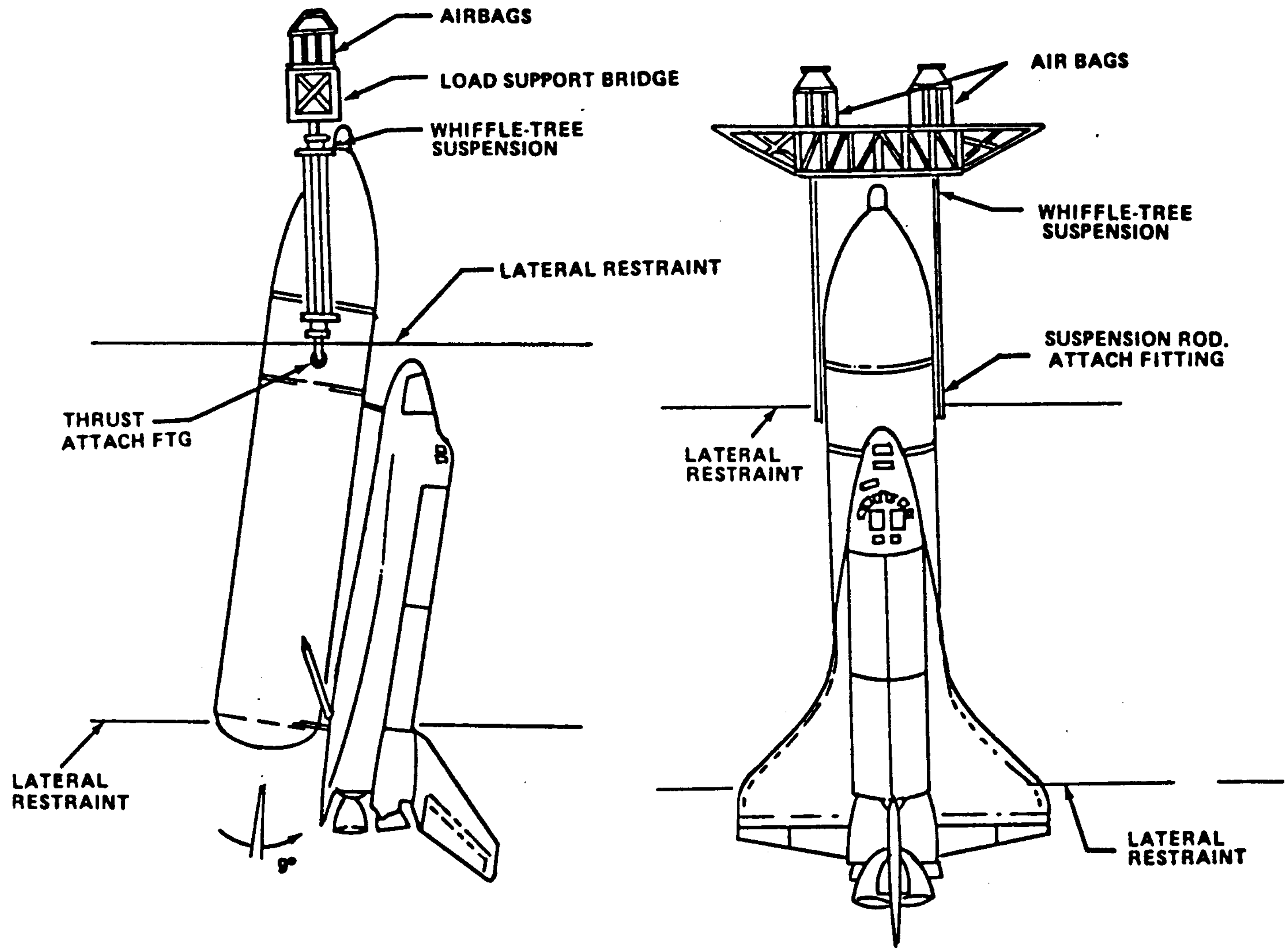


Figure 15. Suspension system for Orbiter/ET boost configuration.

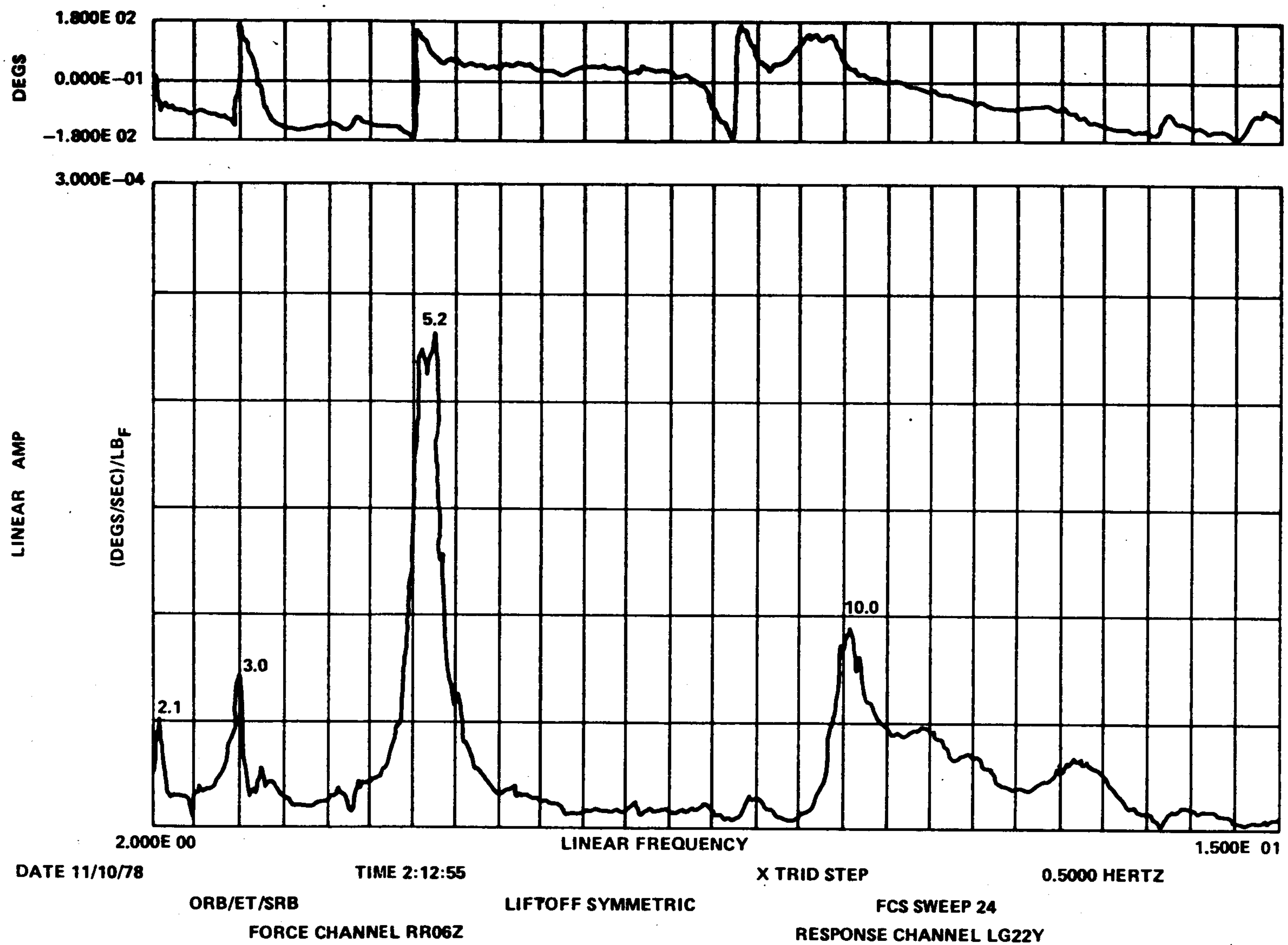


Figure 16. Typical SRB/Orbiter pitch – SRB RGA's.

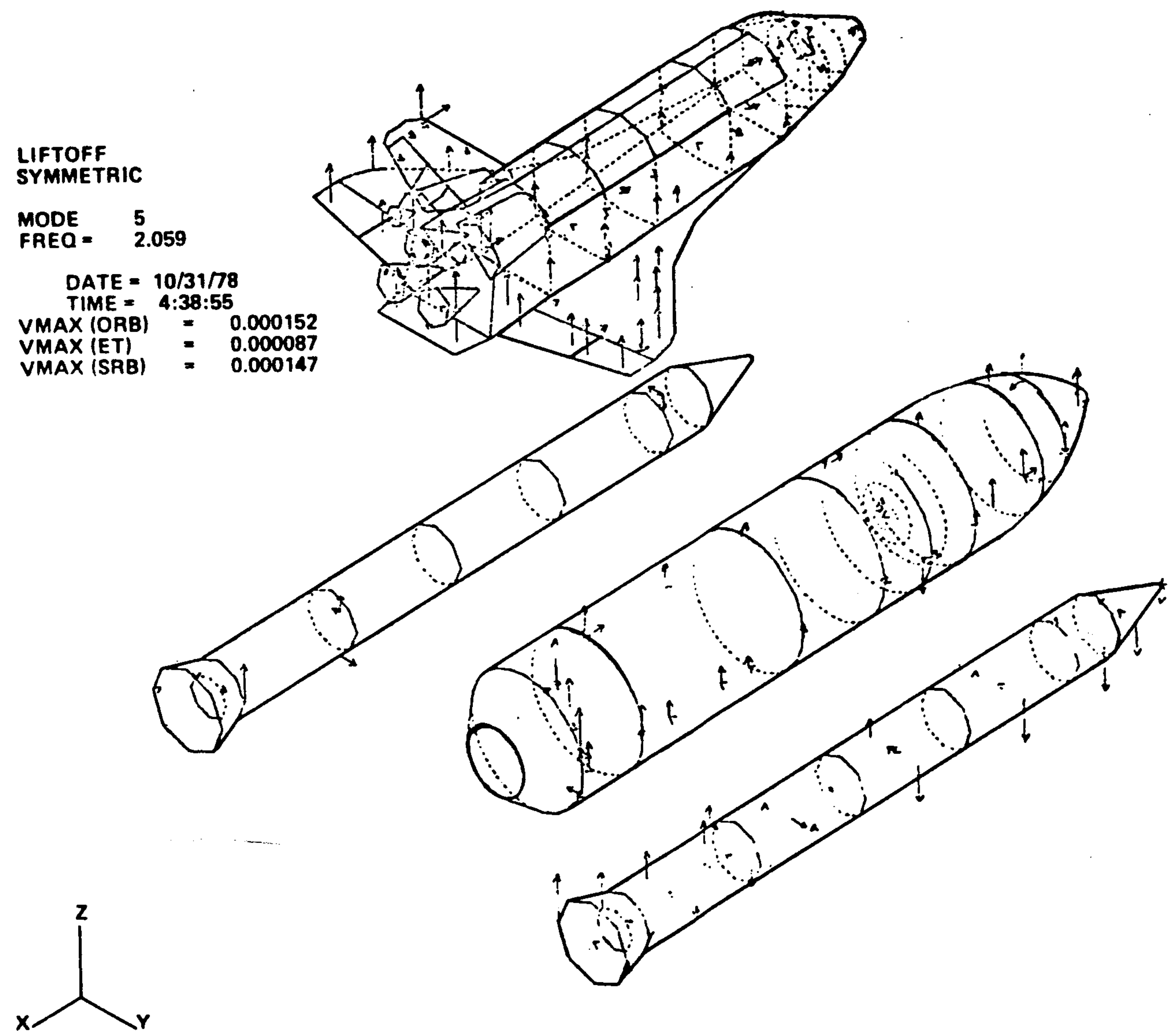


Figure 17. Liftoff symmetrical mode shape.

TABLE 2. MVGVT MODAL CORRELATION, LIFTOFF (SYMMETRIC) CONFIGURATION

Test Mode				Analysis Mode			
Mode No.	Freq.	Damp	Description	Mode	Freq.	Description	Percent Error
5	2.05	.013	SRB Roll (.34), Pitch (.25), Yaw (.16), Orbiter Pitch (.08), ET-Z (.13)	4	2.11	SRB Roll (.38), Pitch (.45), Yaw (.04), Orbiter Pitch (.04), ET-Z (.07)	3
7	2.64	.014	SRB Yaw (.95), ET Pitch (.02)	6 5	2.93 2.45	SRB Yaw (.84), ET Pitch (.02) SRB Yaw (.83), ET Z (.07)	11 8
9	3.02	.017	SRB Pitch (.38), Roll (.27), ET-Z, Bending (.10), Orbiter-Z (.07)	8	3.18	SRB Pitch (.38), Roll (.34), ET-Z, Bending (.06), Orbiter-Z (.08)	5
11	3.24	.010	ORB Bending (.33), X (.36), SRB Z-Bending (.25)	7	3.14	Orbiter Bending (.44), X (.43), SRB Z-Bending (.06)	-3
12	3.88	.015	SRB-X (.60), Yaw (.13), Fwd ET Shell (.24)	9	3.87	SRB-X (.47), Yaw (.38), Fwd ET Shell (.14)	1
23	4.39	.0013	SRB Z-Bending (.22), Roll (.08), F L Fluid (.17), Orbiter Bending (.17)	11	5.16	SRB Z-Bending (.26), Roll (.06), Orbiter Bending (.54)	18[a]
14	5.26	.016	SRB Z-Bending (.47), ET Bending (.27), Orbiter Bending (.17)	12	5.39	SRB Z-Bending (.15), Y-Bending (.13), ET Bending, Axial (.33), ORB Bend (.15)	2
18	5.65	.005	Orbiter Pitch, Bending, In-Phase Wing Bending (.55), Orbiter X (.18)	11	5.16	Orbiter Z, Bending, In-Phase Wing Bending (.54), Orbiter X (.03)	-9
10	6.43	.037	1st Wing Bending (.68), Out-of-Phase Upper SSME (.13)	15	6.60	1st Wing Bending (.64)	3
21	6.78	.011	SRB Sym Yaw and Y-Bending (.85)	18	7.62	SRB Sym Yaw and Y-Bending (.67), Propellant (.12)	12
15	7.02	.011	Vert Tail Fwd Aft Rocking (.21), Out-of-Phase Wing Bending (.18)	16	6.88	Vert Tail Fwd Aft Rocking (.07), Out-of-Phase Wing Bending (.22)	-2
32	7.45	.031	SSME No. 3 Pitch (.20), Out-of-Phase V.T. Fwd/Aft Rocking (.11)	20	8.08	Lwr SSME Pitch (.50), Out-of-Phase V.T. Fwd/Aft Rocking (.41)	8
27	7.77	.009	1st Lox Tank Bulge, Upr LH_2 (.34), Lox Ogive (.14)	18	7.62	Bulge Mode Overwhelmed by SRB Energy	-2
16	8.42	.016	SRB 2nd Z-Bending (.62), Roll (.05)	22	8.36	SRB 2nd Z-Bending (.67), Roll (.08)	-1
13	9.00	.008	Orbiter Pitch and Bending (.76), Out of Phase SRB Pitch (.06)	26	9.40	Orbiter Pitch and Bending (.76), Out-of-Phase SRB (.02)	4

TABLE 2. (Concluded)

Test Mode				Analysis Mode			
Mode No.	Freq.	Damp	Description	Mode No.	Freq.	Description	Percent Error
26	11.94	.025	SRB 2nd Y-Bending (.71), Motor Case No. 3 Prop (.00)	32	10.81	SRB 2nd Y-Bend (.37), No. 3 Prop (.48)	10
				50	14.20	SRB 2nd Y-Bend (.47), ET Y-Bend (.40)	19
22	12.41	.002	Lox Dome Bulge (.0016), F/L (.15), Lox Tank	44	12.99	Lox Dome Bulge (.0064), F/L (.0001), Lox Tank	5
22	12.41	.002	Lox Dome Bulge (.0016), F/L (.15), Lox Tank (.29)	44	12.99	Lox Dome Bulge (.0064), F/L (.0001), Lox Tank (.55)	5
19	14.52	.010	Fwd/Aft P/L X Out-of-Phase (.14), Lwr SSME Pitch (.16)	72	17.89	Fwd/Aft P/L X Out-of-Phase (.31)	23
30	14.87	.022	SRB Torsion (.58), ET (.14)	54	14.73	SRB Torsion (.37), ET (.12)	1
31	14.87	.030	Outb'd Elev Rot Out-of-Phase with Inb'd Elev (.22).	53	14.61	Outb'd Elev Rot Out-of-Phase with Inb'd Elev (.11), SRB Torsion (.30)	2
33	15.97	.008	Lox Dome Bulge (.0066), Lox Tank (.30), SRB Axial (.12)	57	15.15	Lox Dome Bulge (.0025), Lox Tank (.17), SRB Propellant (.42)	5
17	15.97	.027	Payload Pitch (.12), OMS Pod X (.18), ET (.25)				
25	16.15	.012	OMS Pos X (.16), Out-of-Phase P/L X (.07), Crew Mod X (.03) and Z (.05), ET (.28)				
35	18.96	.041	SRB Axial (.43), Lox Dome (.0092), ET (.48)	63	15.90	SRB Axial Out-of-Phase with Propellant (.12), Lox Dome (.0054), ET (.85)	1
36	27.48		SSME Axial, Upr Out-of-Phase with Lwr (.22), OMS Pod (.33), ET (.20)				
39	30.53	.014	SSME Axial, Lwr Out-of-Phase with Upr (.28), OMS Pod (.06), ET (.35)				
34	31.23	.044	Upr SSME Axial (.31), OMS Pod (.19), ET (.24)	169	32.97	Upr SSME Axial (.44), OMS Pod (.07), ET (.16)	6
37	34.74	.018	Upr SSME (.48), Axial In-Phase with Lwr (.01), OMS Pod (.14), ET (.07)	184	36.69	Upr SSME Axial (.56), OMS Pod (.05), ET (.01)	6

1) The left and right SRB forward mounted rate gyros exhibited abnormally high transfer functions, which required a structural redesign.

2) The effect on the frequencies and mode shapes with the SRB stiffening ring on (simulated internal pressure for liftoff) and off was negligible. This lack of difference may have been due to the additional flexibility of the ET at the aft ET/SRB interface. Also, the forward ET/SRB ball joint was found to be "frozen" due to frictional forces on the ball due to the loaded weight of the ET and Orbiter.

3) The SSME axial modes did not correlate well with pretest analysis. The pretest analysis math model was a symmetric half shell. A three-dimensional asymmetric math model of the SSME engines and thrust structure was determined to be required.

4) Pretest SRB Y bending modes for pre-SRB separation did not correlate well with test. This required additional shell modeling of the aft SRB/ET interface.

5) Unexpected large rate gyro yaw rates were observed on the Orbiter 1307 bulkhead during symmetrical (pitch) flight control sweeps. This was found to be due to local deformations and required remodeling of that area.

6) Test rate gyro values showed greater response variations than those used in the analytical studies in determining the redundancy management (RM) trip levels. For STS-1 flight, RM software trip levels and cycle counter levels were increased. The fault isolation routine was modified to inhibit kicking out RGAs and accelerometers after first sensor failure. Changes to the control system for the other flights will be evaluated after STS-1 flight.

A detailed account of the MVGVT and test results will be published in a separate MSFC TM. Rockwell has published detailed reports of test data and evaluation results.

C. Horizontal Ground Vibration Test

The Horizontal Ground Vibration Test (HGVT) was performed by Rockwell International/B-1 Division, Los Angeles, California, during July and August of 1976. The test consisted of the Orbiter OV-101 with the SSME engines and OMS pods simulated by mass and center-of-gravity. The following is a brief overview of the test with an example of the type results obtained. For additional information concerning the test and the test results, Rockwell International should be contacted [13].

The test consisted of a rigid and soft mounted configuration of the Orbiter. The symmetric and antisymmetric modes were obtained utilizing the Shuttle Modal Test and Analysis System (SMTAS) data acquisition.

The rigid configuration (RHGVT) simulated the Orbiter in its attached position to the ET. The soft configuration (SHGVT) simulated a free-free vehicle with the rigid body or suspension system frequencies a factor of five times lower than the lowest vehicle elastic mode. Mode shapes were defined for all resonances between 2 Hz and approximately 30 Hz.

A total of 139 modes were obtained for both tests; however, only 80 modes were considered acceptable. The symmetric and antisymmetric frequencies, mode descriptions, and damping for rigid HGVT are presented in Table 3, as an example of typical results.

A summary of the significant results for HGVT are as follows:

1) Obtaining acceptable response levels was a problem. The fuselage modes were obtained with maximum shaker force levels. However, the response levels were still very low. Shell deformation also occurred at these high force levels, which additionally complicated matters. This situation could not be corrected without changing most fuselage shaker locations to a tangential orientation and adding more shakers.

2) The SSME vertical or axial modes were difficult to define since no shakers were placed directly on the engines.

3) Attempts were mostly successful at defining the DFI and crew cabin component modes since shakers were not attached to these components.

4) The math model of the fuselage must take into account the fuselage shell structures representation rather than a beam representation.

5) The elevon motion predominates in wing as well as elevon modes.

6) Slight differences in frequencies exist between left-hand (L.H.) and right-hand (R.H.) outboard elevons as do R.H. and L.H. speed brakes.

7) Modes involving components and appendages were marginally acceptable due to the low response levels.

D. Quarter Scale Shuttle Test

The quarter scale Shuttle modal ground vibration test program was conducted by Rockwell International/Space Division in Downey, California, under the direction of JSC. The quarter scale model test series consisted of three element and two mated test configurations as follow:

1) External Tank

2) Solid Rocket Booster

TABLE 3. MODE SUMMARY DATA SYMMETRIC RHGVT

Test Mode	Frequency (Hz)	Damping (Viscous) (%)	Mode Description
28	3.654	5.4	1st Fuse. Vert. Bend with in phase Vert Tail pitch
2	6.633	8.8	1st Wing Vert. Bend
3	7.610	6.2	Mid Fuse. Vert. Bend with elevon rotation
7	7.988	2.4	#1 SSME Vert. translation with out/phase vertical tail fore/aft bending
19	8.635	3.0	Vehicle axial translation with out/phase vertical tail fore/aft bend and DFI axial trans.
25	10.30	-	#2 & #3 SSME vert. trans. with out/phase vertical tail fore/aft bend
23	11.58	12.0	#2 & #3 SSME lateral out/phase trans.
27	12.19	6.2	2nd Fuse. Vert. Bend with DFI axial and crew cabin axial motion out/phase
5	12.76	11.0	Inb'd Elevon Rotation with out/phase body flap rotation
6	16.78	-	R.H. Outb'd Elevon Rotation; L.H. rotational frequency slightly different
18	17.684	7.2	DFI vert. trans. component mode with 3rd fuse. vert. bend.
22	18.05	-	L.H. & R.H. Speed Brake out/phase rotation; L.H. Speed brakes better accel. phasing than R.H.
20	19.04	7.2	R.H. Outb'd Elevon Rotation/Roll Bending in phase body flap; L.H. slight diff.
8	20.61	8.8	R.H. Outb'd Elevon Roll Bending; L.H. roll bending frequency slightly different
11	26.26	7.2	Inb'd Elevon Roll Bending
10	28.76	8.8	1st Wing Torsion with Inb'd elevon roll, outb'd elevon rotation/bending; accel. phasing marginal
16	29.119	2.8	SSME's Pitch-Bending Mode with #2 and #3 SSME axial motion
24	31.77	4.4	2nd Vertical Tail Fore/Aft Bending with #1 SSME axial motion
13	34.165	11.0	Wing higher bending mode
12	36.89	8.8	1st Body Flat Spanwise Vertical Bending

3) Orbiter

4) Orbiter/ET — 13 degree tilt

   a) Post SRB separation

   b) Mid-burn

   c) End burn

5) Orbiter/ET/SRB

   a) Liftoff

   b) Max q

   c) Pre-SRB separation.

The test began on November 15, 1976, and was completed December 10, 1977. The test articles were all supported by a soft suspension system. The Orbiter contained a rigid payload, which simulated a flight payload of 32,000 pounds. The External Tank lox tank contained water which was adjusted to correspond with the flight event tested. The LH_2 tank was empty. The SRBs were loaded with an inert mixture which represented the solid propellant.

The summary objectives of the quarter scale model ground vibration test program were [13,14]:

1) To verify the dynamic math models of the quarter scale replica Shuttle models of the Orbiter, ET, and SRB elements, separately and coupled. This included verification of mathematical techniques for modal synthesis.

2) To experimentally obtain the transfer functions at the Orbiter guidance sensor locations for the mated Orbiter/ET and Orbiter/ET/SRB configurations.

The symmetric and antisymmetric modes for each test configuration were obtained and documented by Rockwell. The lift-off symmetric test frequencies, damping and analysis correlations are listed in Table 4 and are typical of the results obtained from the quarter scale test.

For additional information concerning the test articles, the suspension system, data acquisition, or test results for each of the five test configurations, Rockwell International/Space Division in Downey, California, should be contacted [1-6,15,16].

TABLE 4. QSGVT LIFT-OFF SYMMETRIC MODES QUICK LOOK SUMMARY

Mode Sequence No.	Test Mode No.	Frequency (Hz)	Analysis Frequency (Hz)	Test Mode Description (Dominant Motion)	Damping Value (C/Cc)
1	44	6.71	8.04	SRB Roll (0.38) and Pitch (0.18) (Repeat of Test Mode 13 at 226 lb Force)	0.044
2	45	7.00	8.04	SRB Roll (0.33) (Repeat of Test Mode 13 at 143 lb Force)	0.032
3	13	7.29	8.04	SRB Roll (0.33) and Pitch (0.18) 63 lb Force	0.036
4	12	10.46	10.22	SRB Yaw (0.95)	0.008
5	4	11.06	12.54	SRB Pitch (0.51) and Roll (0.13) two Shakers per SRB	0.04
6	43	11.12	12.54	SRB Pitch (0.49) and Roll (0.12) one Shaker Per SRB	0.028
7	6	11.71	12.42	ORB Pitch (0.62), SRB Roll (0.13) and Yaw (0.13)	0.015
8	23	12.70	N/A	First Feed Line Fluid	0.013
9	8	15.77	17.39	SRB Axial (0.45) and Yaw (0.35), and ET Lox (M=2, N=2)	0.008
10	9	20.84	26.41 22.76	ORB Axial (0.24) SRB First Z Bending (0.29) SSMEs Pitch (0.21)	0.018
11	1	22.72	22.76	SRB First Z Bending (0.40), Eng's θy (0.17) and ET 1 Z (0.15)	0.018
12	2	25.63	27.8	ORB Wing Z Bending (0.90)	0.015
13	14	26.92	30.84	Vert. Tail Pitch (0.40) and Eng. No. 3 Pitch (0.33)	0.017/ 0.027
14	16	27.48	32.36	SRB First Y Bending (0.95) and Wing Z	0.007
15	11	29.68	34.83 35.71	ORB Pitch (0.41), Wind Bending (0.12), and SRB Yaw	0.008
16	10	32.23	31.75	ET Lox (M=1, N=5), (0.77)	0.005
17	21	32.23	32.19	ET LH_2 Shell (0.12), Lox Shell (0.10), Dome Axial (0.10), Body Flap (0.18)	0.016
18	26	34.08		Body Flat (0.35), Dome Out-of-Phase w/Lox Line	0.010

TABLE 4. (Continued)

Mode Sequence No.	Test Mode No.	Frequency (Hz)	Analysis Frequency (Hz)	Test Mode Description (Dominant Motion)	Damping Value (C/Cc)
19	7	35.31	35.25	SRB Second Z Bending (0.34) ET Z Bending (0.37), Body Flat Rotation (0.12)	0.007
20	42	42.86		Fus. Z Bending (0.12) and Crew Cabin X (0.33)	0.014
21	3	46.85	49.15	SRB Second Z Bending (0.57) ET LH_2 Tank (M=1, N=2) (0.19)	0.014
22	17	48.97	54.17	SRB Second YBending (0.88)	0.017
23	28	52.78	54.17	Lox Dome Axial (0.25), LH_2	0.006
24	31	54.47	45.98	Fus. Z Bending (0.82), LH_2 (M=1 N=3) (0.16)	0.010
25	29	56.96	65.15 65.39	SRB Torsion (0.20) ET Shell (0.51)	0.006
26	15	60.68	65.39	Lox Tank (M=2, N=2), Dome X (0.98)	0.003
27	5	63.27		Low Pressure Pumps X (0.18), Eng No. 1 Pitch (0.09)	0.019
28	39	66.03	62.11	SRB First Axial (0.65), Tuned at Max. Quad	0.092
29	38	70.11	74.98	SRB First Axial (0.48), Lox Shell (0.18) Tuned by Closing Lissajou	0.11
30	22	73.90	72.56	SRB Third Z Bending (0.25)	0.036
31	36	74.98		Eng. No. 1 Axial (0.40), Payload X (0.12)	0.018
32	18	75.41	79.37	SRB Third Y Bending (0.85)	0.040
33	24	82.11		LH_2 Z Bending (0.36), Dome X (0.05)	0.027
34	37	83.55	83.72	OMS RCS X (0.17), Lox Pumps (0.10), OMS Prop. X (0.07)	0.022
35	33	90.09		Eng No. 3 X (0.19), Lox Pump Axial (0.13)	0.037
36	25	91.64		Eng Pumps X (0.26), Eng. 3 Out-of-Phase W/Eng 1 X (0.14)	0.022
37	27	95.56	101.77 98.94	Wing Torsion (0.35) SRB Fourth Z Bending (0.16)	0.027
38	20	99.76	102.55	SRB Fourth Y Bending (0.63)	0.073

TABLE 4. (Concluded)

Mode Sequence No.	Test Mode No.	Frequency (Hz)	Analysis Frequency (Hz)	Test Mode Description (Dominant Motion)	Damping Value (C/Cc)
39	41	116.1	*	SRB Nozzle Axial (0.78)	0.073
40	34	121.85	111.99	Eng. No. 1 Axial (0.40)	0.016
41	32	129.05		Eng. No. 3 (0.32) Out-of-Phase w/Lox Pump Axial, LH_2 (M=2, N=2) (0.11)	0.037 0.037
42	35	157.3		Eng. No. 1 Axial (0.22), LH_2 Pumps X (0.57)	0.025
43	40	173.89	*	SRB Nozzle Axial (0.86)	0.028

* The SRB axial mode will be investigated further during the pre-SRB separation test.

E. SRB Dynamic Model and Test Including Viscoelastic Propellant Effects on Space Shuttle System Characteristics

In early studies, viscoelastic effects were determined to be significant only in the longitudinal mode. This result was due to the massive SRB attachment ring frame. Internal pressure was found to be negligible for the same reason. In order to reduce weight and get more clearance, the attachment ring was redesigned. Analysis of this redesigned SRB showed that analytically derived assumptions on pressure and viscoelastic effects were no longer true for vehicle systems modes that had a lot of local deflection of the aft SRB to ET attach point.

At this point in time, the SRB full scale element test had been eliminated. Restoration of this program would have been very costly and nearly impossible, schedule wise, due to hardware availability. This meant that verification of the SRB model and these effects must rely on the coupon, SRB quarter scale element test, and the quarter scale and full scale systems tests. A special quarter scale element test was instituted to verify pressure effects.

This section deals with two categories of solid propellant dynamics that are of concern in Space Shuttle dynamics definition. The first is longitudinal propellant oscillation (pogo coupling modes), and the second is propellant stiffness effects on SRB/ET interface and associated system modes.

1. Propellant Properties Research and Measurement. Several investigations have been conducted to determine propellant mechanical properties; shear modulus, tensile modulus, Poisson's ratio, and compressibility. These quantities are complex numbers. Shear modulus is:

$$G = G' + iG'' \quad ,$$

where G' is called the storage modulus and G" is the loss modulus. The ratio G"/G' represents material damping and can be on the order of 0.5. These parameters are measured primarily by the "coupon" test (Gottenberg oscillating disk) and by the lap shear dynamic test. In either case, the applied force, response, and phase relationships are recorded and used to compute the components of dynamic modulus. The property measurements used as input to the SRB math model have been determined through the expected Shuttle range of excitation frequency and temperature. A graph of G' versus frequency for three temperatures is shown in Figure 18 for the SRB live propellant.

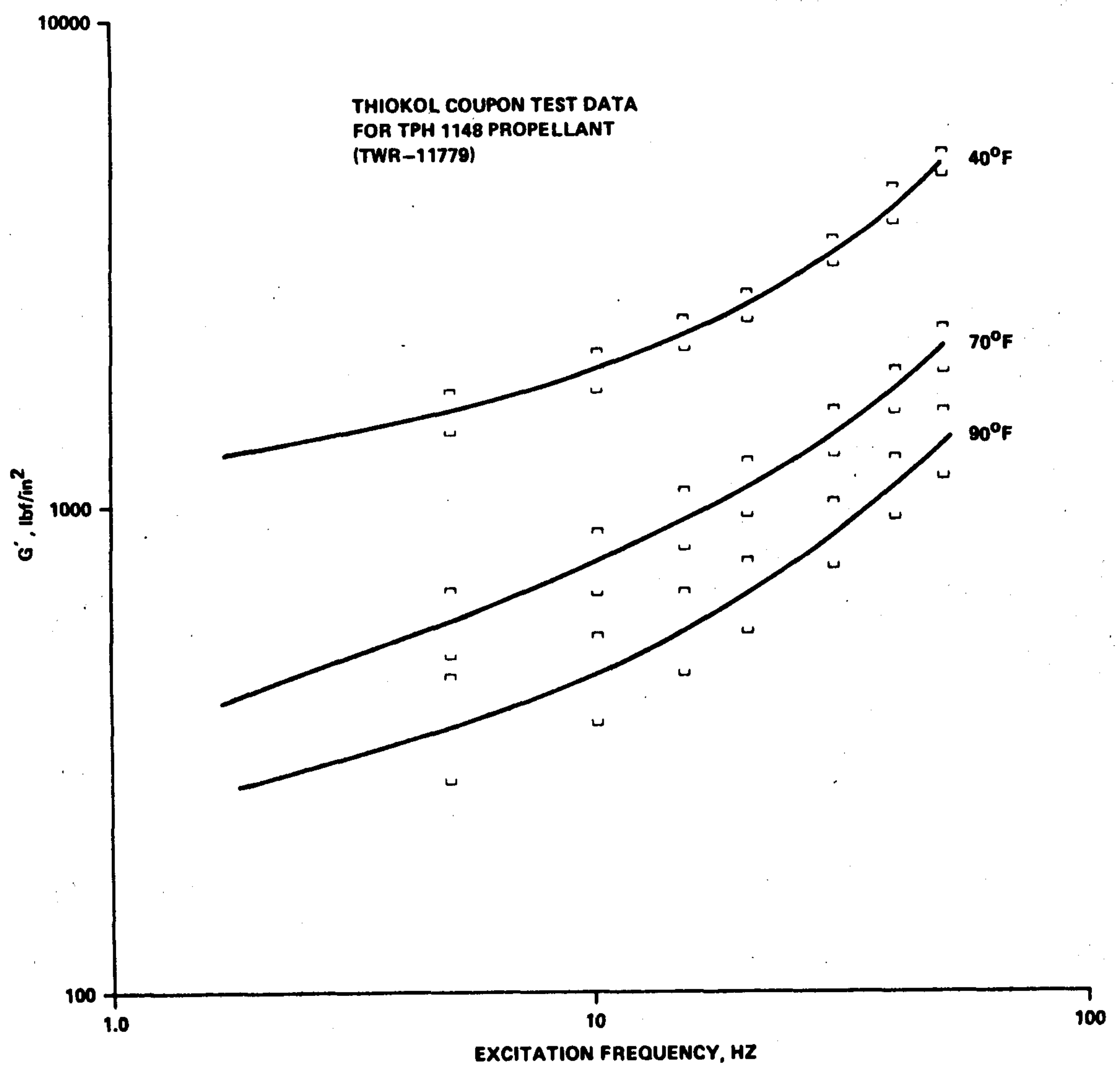


Figure 18. Coupon derived propellant characteristics.

Many variables affect solid propellant properties. Some of those investigated and found to be unimportant or avoidable for the Shuttle application are:

a) Humidity

b) Strain

c) Pressure

d) Aging

e) Epoxy/curative ratio

f) Internal heat generation

g) Damage effects.

2. Propellant/SRB Longitudinal Interaction. Longitudinal propellant dynamics were first analyzed in the Shuttle Program using a computer model with solid ring elements to represent propellant. Some typical modes from this model are shown in Figure 19.

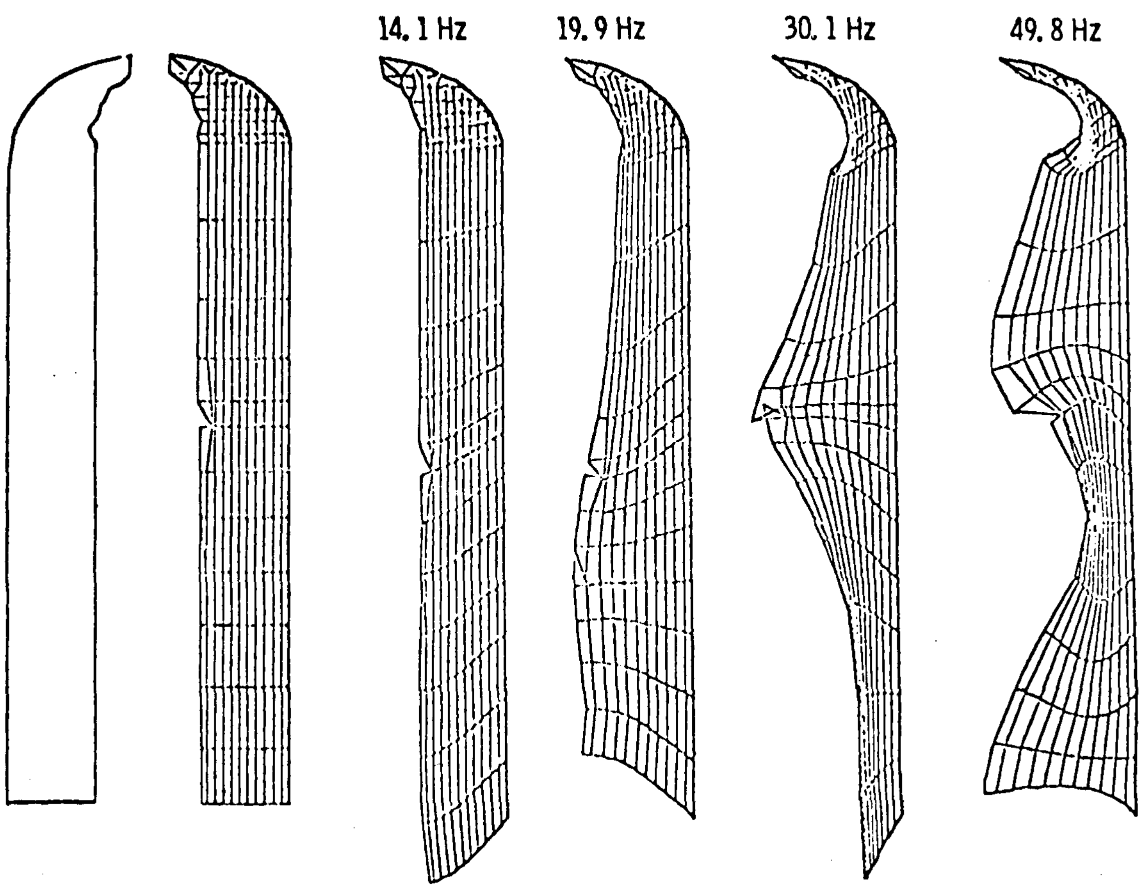


Figure 19. Mode shapes of solid propellant.

The two modes with largest generalized mass for each of the four SRB casting segments were represented in simplified form in the early (pretest) SRB math models. During quarter scale testing and MVGVT full scale testing, it was found that the high propellant damping eliminates longitudinal propellant modes. Current SRB dynamics math models have been greatly simplified by the deletion of these longitudinal propellant modes as justified by test results.

3. Propellant Effects on SRB/Shuttle System Interface Stiffness. The most important effect of propellant on Shuttle modes is due to the dependence of ET/SRB interface stiffness on propellant shear modulus. A detailed SRB model (9000 DOF) was developed to properly represent stiffness while maintaining accurate structural SRB modes. The effect of shear modulus on the frequency of an SRB Z translation/roll mode is shown in Figure 20. Several of the Shuttle system modes at low frequency show similarity to this mode. The ability of the math model to accurately predict this type mode was verified by quarter scale SRB test and by full scale MVGVT.

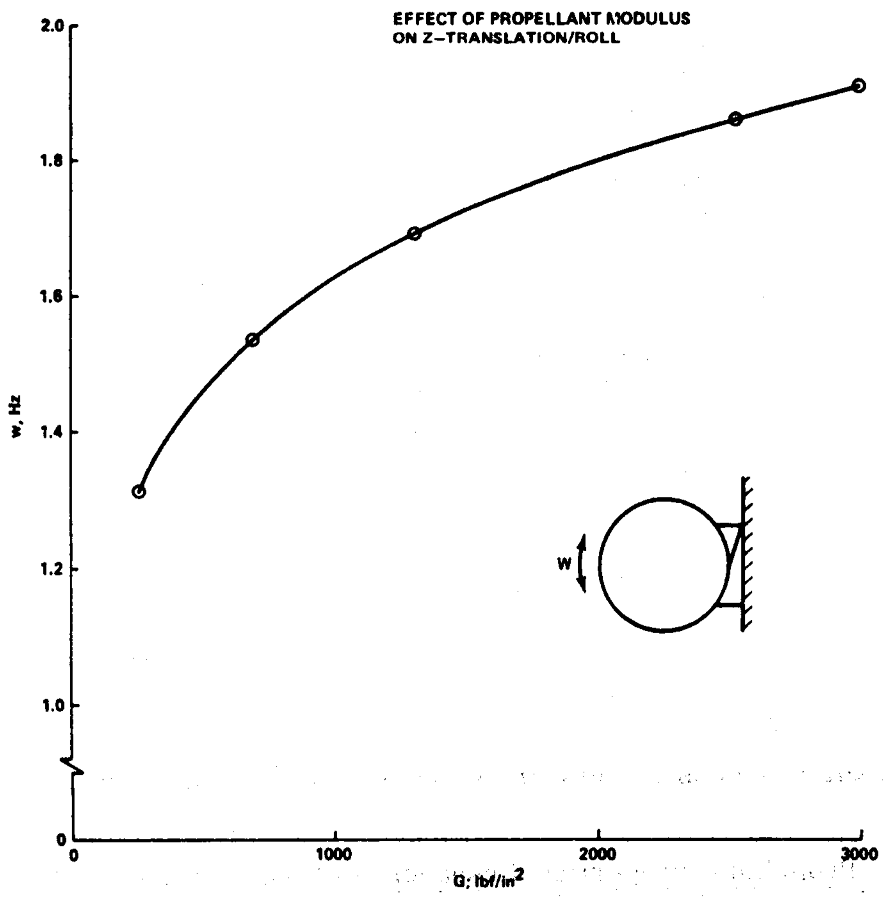


Figure 20. Propellant modulus effect on interface stiffness.

Internal pressure of the motor case stiffens the aft SRB/ET interface in a way similar to propellant shear stiffness. An effort was made to compute this effect using the differential stiffness solution option in the NASTRAN and SPAR computer programs. This computation routine applies pressure loading to the motor case and determines hoop stresses. The stresses are used to calculate additional stiffness, which is then added to the original stiffness matrix. The new complete matrix is then used to compute modes and frequencies. In each case, the pressure stiffening prediction was too great compared to test results. Attempts were made to find the cause of this discrepancy, but to no avail.

The effect of pressure on the Z translation/roll mode frequency, as measured in the quarter scale SRB element test, is shown in Figure 21.

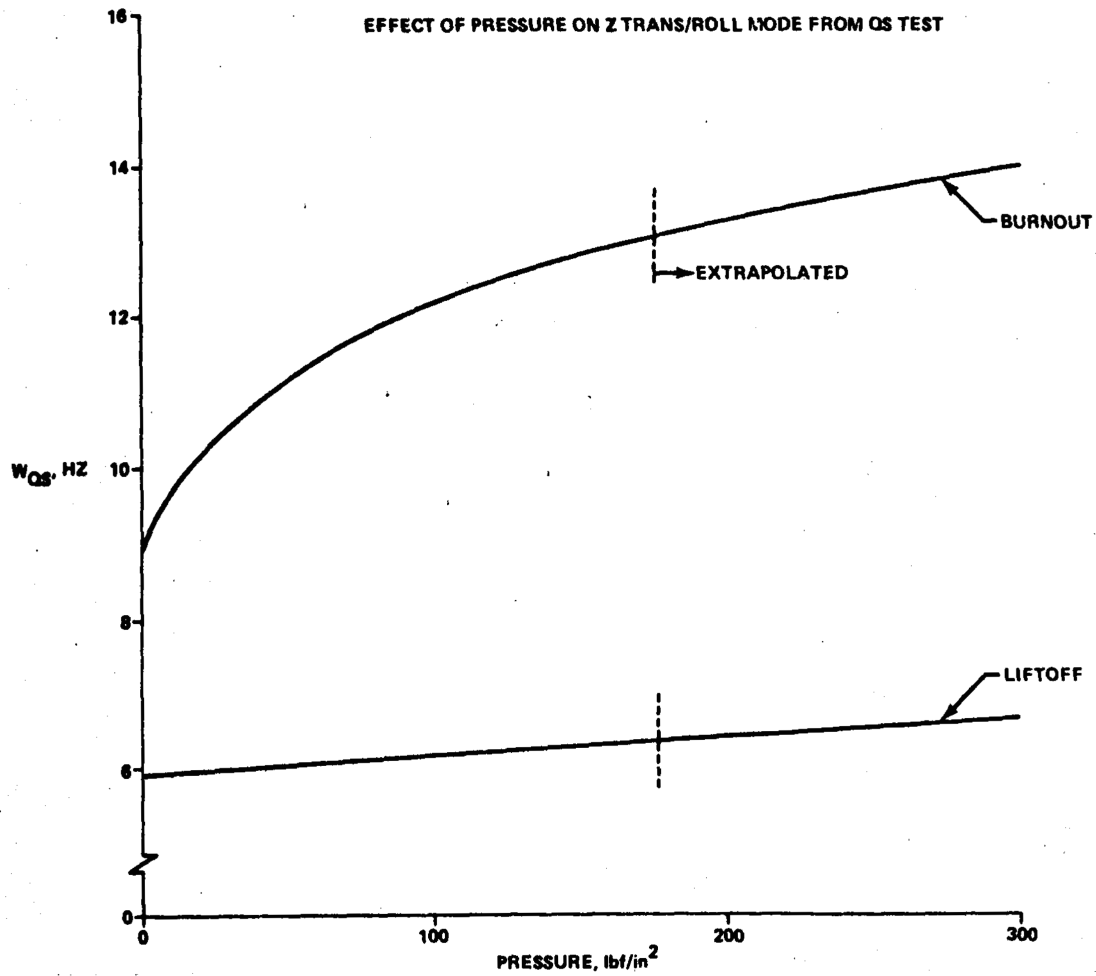


Figure 21. Pressure effect on interface stiffness.

Although pressure stiffening is not related to propellant, the effect is similar; therefore, an increment of propellant shear modulus was added to the actual shear modulus as input to the math model to represent pressure stiffening. The amount of pressure stiffening required was determined empirically from a quarter scale test.

F. ET LOX Modal Survey

A modal survey (February-July 1978) of the liquid oxygen tank coupled to the intertank was performed at MSFC to determine the hydroelastic modal characteristics. The objective of the test was to obtain sufficient data to verify a portion of the analytical model used in the "pogo" prevention plan. The test was successfully completed, and the model results proved to be extremely accurate.

The test article consisted of a full scale flight LO_2 tank and intertank mated to a stiff support test ring fixture, which mass simulated the empty LH_2 tank. The test article was supported in a soft spring mode by 33 airbags arranged in three groups. Fourteen Unholtz-Dickey Model 6 (1,000 force-pound) shakers were used to excite the modes (3 to 50 Hz), which were considered to be prime pogo oriented modes, together with the normal bending modes. There were 202 Kistler servo-accelerometers used to measure the structural response of the test article. Five Piezontronic, Inc., dynamic pressure transducers were installed on the inside-skin-line of the aft dome to measure transient pressures (Fig. 22).

The test conditions were selected to be representative of the flight configuration. Four fluid (H_2O) levels were selected to represent liftoff, SRB separation, mid-range flight, and end burn. The liftoff configuration was tested in a vertical position (zero cant), while the last three original test configurations were tested at a canted angle of 13 degrees measured from the vertical. The 13-degree canted attitude was used to obtain the correct relationship of the fluid surface to the tank wall due to the thrust vector being maintained through the Shuttle center-of-gravity. Additional test conditions were added as the test progressed to obtain a better understanding of the low damping (ζ = 0.17 percent) observed in the test results of the second aft dome bulge mode [17,18].

The test configurations were investigated by using wide band sine sweeps over the range of interest (3 to 50 Hz) and co-quad plots were made. Discrete frequencies and mode forms were identified from these plots. Utilizing an extremely accurate pretest analysis result, the prime pogo oriented modes were identified. The frequency of each significant mode was tuned until an acceptable force-response/phase relation was achieved; modal dwells and decay functions were then recorded on magnetic tape and on an on-line computer data storage unit. Modal dwell data were processed by the MSFC Computer Services Office into a tabular

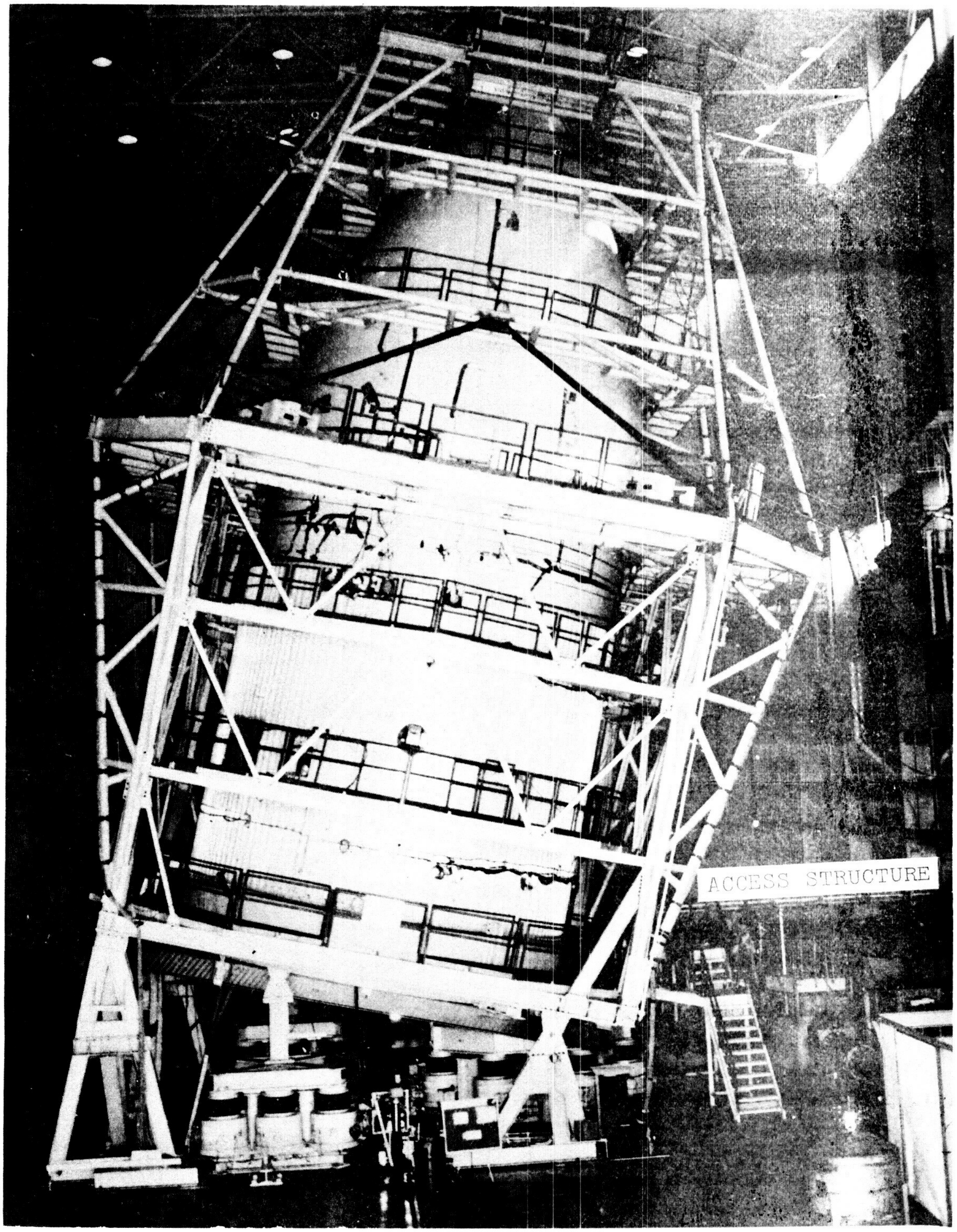


Figure 22. LO_2 modal test setup (cant angle 13°).

listing of the acceleration and phase response of each instrument and normalized mode shape plots of the test article. Typical examples of the analysis and test correlation of frequency and damping are shown in Table 5.

TABLE 5. ET LOX MODAL TEST DATA COMPARISON OF FREQUENCY AND DAMPING MULTI-POINT SINE VERSUS SINGLE POINT RANDOM

Analysis Mode No.	Frequency (Hz)			Damping (C/C_c)[a]		Mode Description
	Analysis	MPS	SPR	MPS	SPR	
10	5.00	4.88	4.794	0.016	0.0032	M1, N2; Shell (A)
12	4.75	4.90	4.969	0.016	0.0185	M1, N2; Shell (S)
11	4.39		5.261		0.0197	M1, N2; Shell (S)
			5.655		0.0155	
13	5.16	5.72	5.853	0.022	0.0158	M1, N0; Bulge (S)
			8.867		0.0021	M1, N5; Shell (S)
19	8.91	9.04		0.011		M1, N1, Bending (S)
29	9.68	9.18	9.193	0.00319	0.0026	M2, N3; Shell (S)
16	8.93	9.48	9.407	0.0067	0.0057	M1, N1; Bending (A)
		9.75	9.336	0.020	0.0122	M2, N7; Shell (S)
			9.432		0.0177	Shell
			9.767		0.0075	Shell
26	12.96	12.76	12.748	0.00174[b]	0.00144	M2, N0: Second System Bulge
			12.832		0.00238	Shell and Bulge
			13.075		0.00898	Shell and Bulge, Ogive
			13.332		0.0010	Shell, Ogive
			13.650		0.00535	Shell and Bending
22	12.79	13.73		0.003		M2, N1; Bending and Shell
			13.798		0.002	
27'	13.17	14.08	15.057	0.00165	0.00338	M2, N1; Bending (S)
			14.528		0.0045	Shell
			14.578		0.0047	Shell
			14.736		0.0009	Shell and Ogive Bulge
			14.877		0.0033	
			15.240		0.0077	
			15.517		0.00137	
			15.760		0.00195	
			15.907		0.0038	
			16.139		0.0053	
			16.240		0.0012	
32	15.30	16.54	16.603	0.00323	0.0030	Bending (S)
		16.56		0.0029		Dome Bending and Ogive Shell
75	14.80	16.63	16.460	0.0030	0.0027	M3, N1; Bending (A)
			16.950		0.0079	Shell

a. All damping values are average from on-line measurements.
b. Average system damping. Aft dome measurements indicate 0.11 percent damping.

Figure 23 shows the change in damping for the second LO_2 tank bulge mode damping. Values for various cant angles and fill conditions are shown. Notice that for the near full conditions the damping is very low, around 0.2 percent critical. As lox is drained off, the damping increases dramatically reaching 1.2 percent. Then linearity decreases with further lox depletion. This is a significant finding since any forced oscillation near 12 Hz would create large responses.

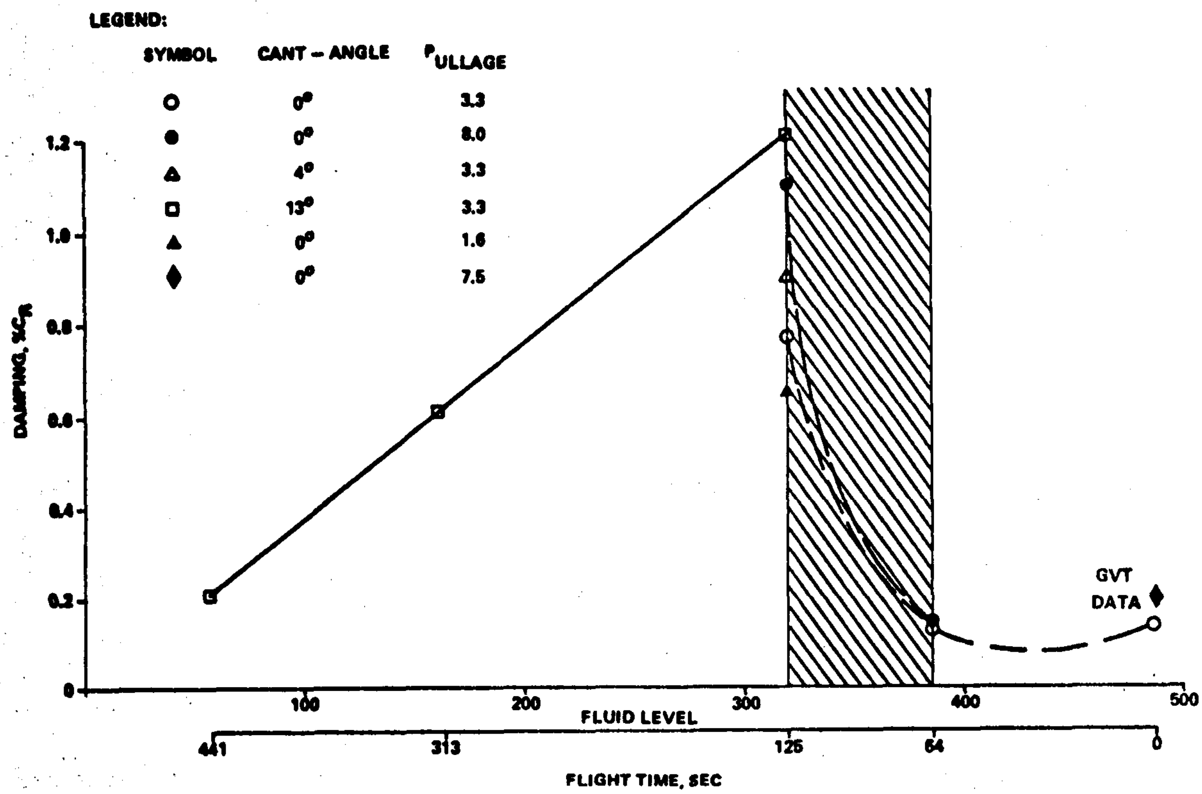


Figure 23. Second LO_2 tank bulge mode damping.

The overall analytical ability to predict these bulge modes is depicted in Figure 24. Frequency versus modal or frequency order is plotted. Other than the third bulge mode, the results are excellent.

During the test, some of the modes of primary interest were difficult to tune due to shell modes coupling and low modal damping. To assist in overcoming this problem, single-point random (SPR) tests were performed for each of the test conditions. Excitation for the SPR testing was provided by a Hewlett-Packard 5425 vibration control system. The drive spectrum was a shaped 5 to 50 Hz bandwidth ranging in composite force from 93 to 150 RMS force-pounds. Data were acquired with the

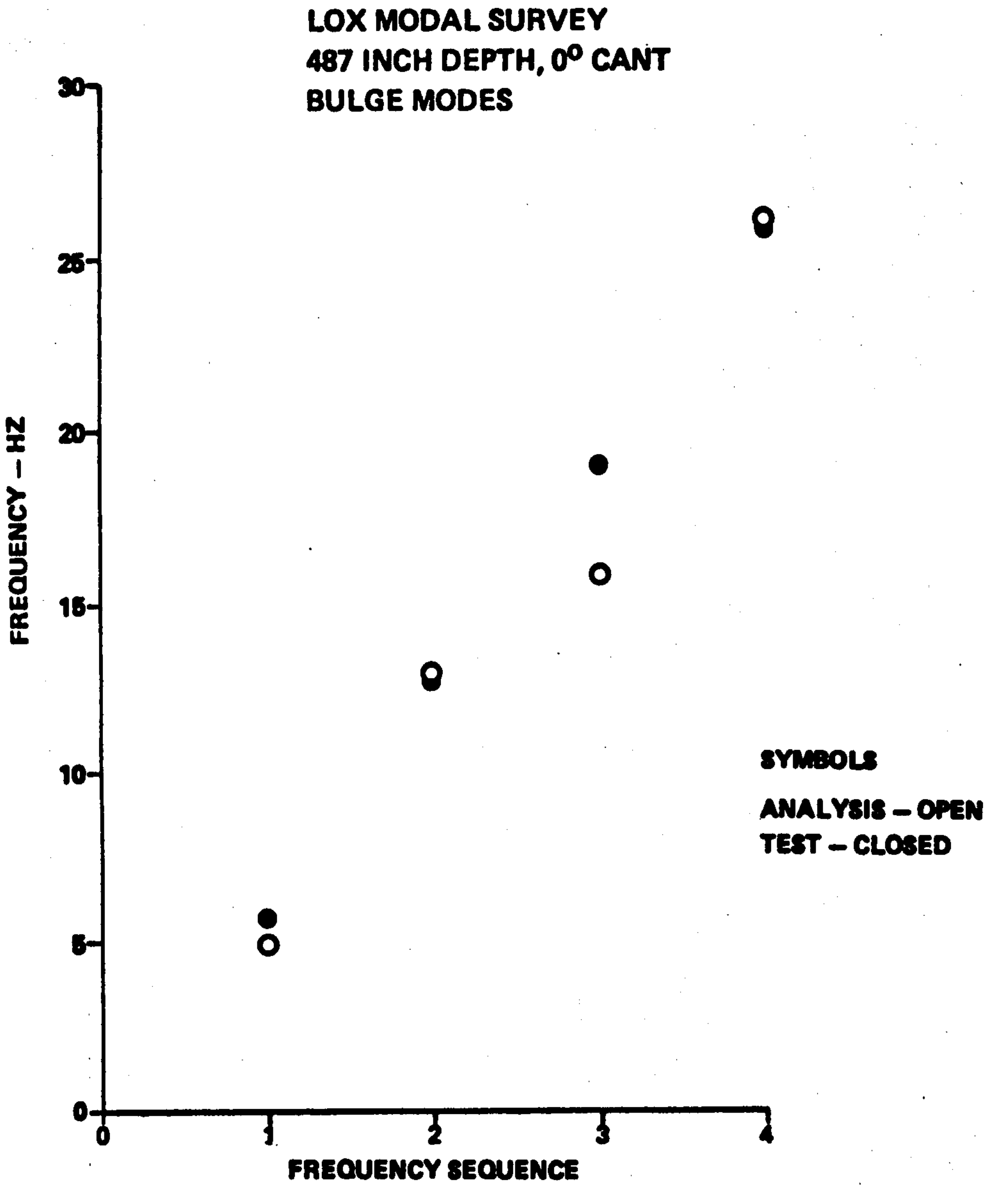


Figure 24. Lox modal survey bulge modes.

same Hewlett-Packard 5451B modal system used in the multiple point sine test. Approximately 30 minutes of data were recorded for each measurement and stored on magnetic tape for later analysis. The data were processed and analyzed employing a least square curve fitting algorithm to obtain mode shapes and modal coefficients. Results are shown in Table 5.

Agreement between the two techniques is good. In general, the single-point random produces many more modes, particularly where there is high modal density. In conclusion, the test was highly successful, bringing out the low damping in the bulge mode and showing good analytical test correlation. The value of having more than one test approach was exemplfied. The power of the single-point random to isolate closely grouped modes was demonstrated.

G. Main Engine Structural Dynamic Test and Pogo Characteristics

The pogo characteristics, as mentioned earlier, were determined in three basic ways: (1) overall vehicle longitudinal modes in quarter scale and MVGVT, (2) engine and propulsion system structural coupling in MPT random modal survey, and (3) propulsion system engine structural coupling in MPT and single engine hot firings. The Shuttle main engine also had several key structural dynamic problems that eventually led to special dynamic tests. There were (1) total engine system impulse test, (2) nozzle random modal survey, (3) high pressure lox pump case, and (4) power head lox post test. This section discusses these dynamic test programs and the pogo testing programs.

The total engine system impulse/rap test was conducted by SDRC to determine the effects of coupling the nozzle, power head, and high pressure pumps on the modal characteristics of an individual pump. This was important in the stability analysis of the whirl problem and in the high pressure fuel pump bearing loads/lifetime analysis for both the high pressure fuel and lox pumps. The approach was to rap the engine and let it go into a free decay condition from which the modal characteristics could be determined. Using this approach was very advantageous since an engine could be rapped while in the test stand in its hot firing configuration. This allowed the test without special hardware and minimum schedule impacts. The only down time from hot firing was for instrumentation installation and the test time. With smaller systems where large or special force application (multi-point) is not a requirement, this is a very good approach. The results showed that the cross coupling between pumps through the power head was important. A detailed analytical model was constructed and correlated to the test data. This model serves as the basis for the stability and response simulation and matches well the hot firing results.

On two main engine hot firings, the hydrogen propellant coolant line to the nozzle failed. It was found that during engine start and shutdown, when the nozzle is not filled, large side loads and shock loads are imparted to the nozzle. These forces excited high ordered nozzle shell modes and various coolant line (steerhorn)modes leading to fatigue. Figure 25 shows a typical hot firing acceleration output spectrum measured on the nozzle manifold showing response in all shell modes with the largest amplitude occurring for N = 6. The N = 6 mode is shown on the figure as well as the frequency range of modes versus N — number noted is the N = 0 mode at 250 Hz, which is closely coupled with the N = 6 mode.

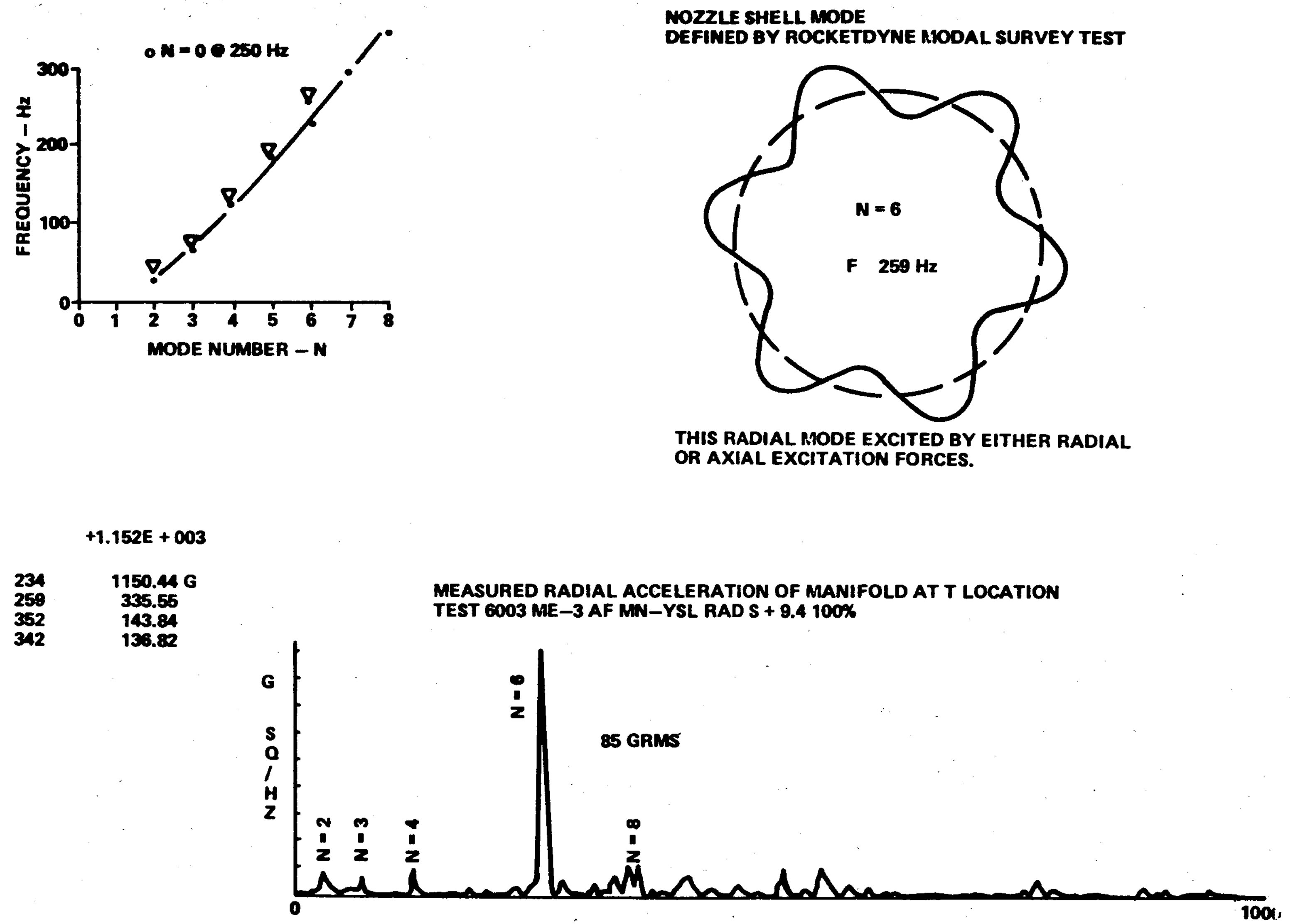


Figure 25. Typical hot firing acceleration output spectrum.

In order to redesign and verify a coolant line redesign, two activities were required: (1) accurate definition of the forcing function and (2) accurate verification of the complex modal characteristics of the nozzle coolant line configuration. The scale model flow test to determine the forcing function was done by Rocketdyne and is not a part of this report. The dynamic test of the nozzle was conducted at MSFC using the single point random approach. In parallel with the dynamic test, an analytical math model was developed and correlated to the dynamic test. This was used to (1) verify end to end, pressure to stress response at structure and understand the total system, and (2) verify the performance of short-term and long-term modifications of the system.

Figure 26 is a schematic of the nozzle showing one downcomer. The nozzle is a brazed tube bundle, partially jacketed, and reinforced with hatbands. The downcomers and steerhorns distribute the coolant fuel to the aft manifold and then flows into the nozzle tubes and back into the propulsion system.

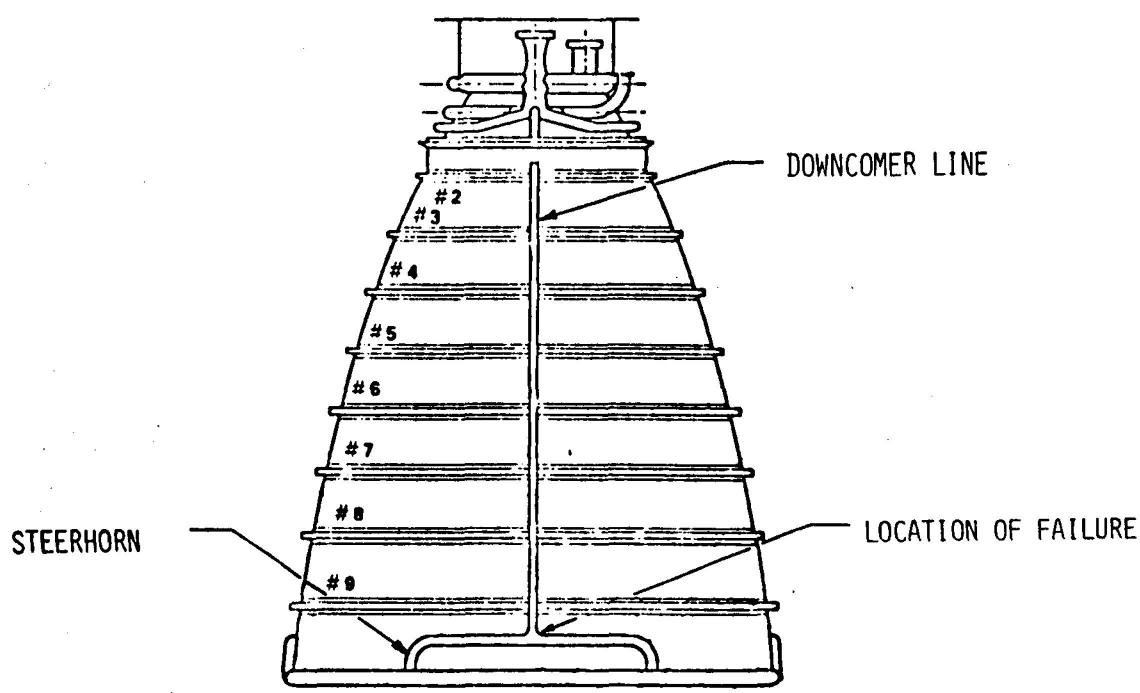


Figure 26. Description of nozzle system.

A detailed modal survey was done with this nozzle configuration using the single point random approach. A detailed test plan with objectives, requirements, and instrumentation was developed and documented in DST-SSME TIP-0001, SSME Steerhorn and Nozzle Assembly Test, dated December 19, 1979. Ten input force locations/directions combinations and up to 245 measurement locations, each triaxial accelerometers, were used. Table 6 summarizes these test conditions. Since the coolant tubes are pressurized, it was necessary to determine pressure effects on modal characteristics.

TABLE 6. ORDER OF MODAL SURVEY TESTS

Condition	Nozzle Input			Steerhorn Input				Quarter Segment Panel
	0° RAD	0° AX	45° RAD	No. 1 RAD	No. 1 AX	No. 3 RAD	No. 3 AX	
Unpressurized	1 245	10 245	4 245	2 62	3 62	8 67	7 67	9
Pressurized 200 PSI 500 PSI	1 5 48							
Pressurized 1000 PSI 2000 PSI	6 48							

RAD Radial
AX Axial
Figure within box indicates number of accelerometer locations

Input control and data reduction was done using a Hewlett-Packard 5427 with University of Cincinnati software. The system operation was reliable and accurate, although capacity was taxed by the large number of instruments, the large bandwidth (0 to 500 Hz), and the high modal density.

Figure 27 is a picture of the instrumented nozzle suspended in the test facility.

The dynamic test program included 10 different single point random excitations, high force sine dwell of three modes, and a "twang" test to simulate the pressure impulse. The most significant results from the test were findings of very low structural damping, and large amplitude response at the upper parts of the LH_2 feedline.

Detailed models of the tube bundle were required to obtain the equivalent shell coefficients. All-shell models of the nozzle wall were found better than beam-shell models. The total structure was found to have 200 modes in the frequency range of interest, 0 to 500 Hz. The modes were calculated on the MSFC Univac 1100 computer using symmetric and antisymmetric half models and using the SPAR program. A 1/6 segment model was also used during much of the investigation. The N = 6 mode found in test is shown on Figure 28.

The test derived frequency response for one input and accelerometer output shows the large model density (Fig. 29).

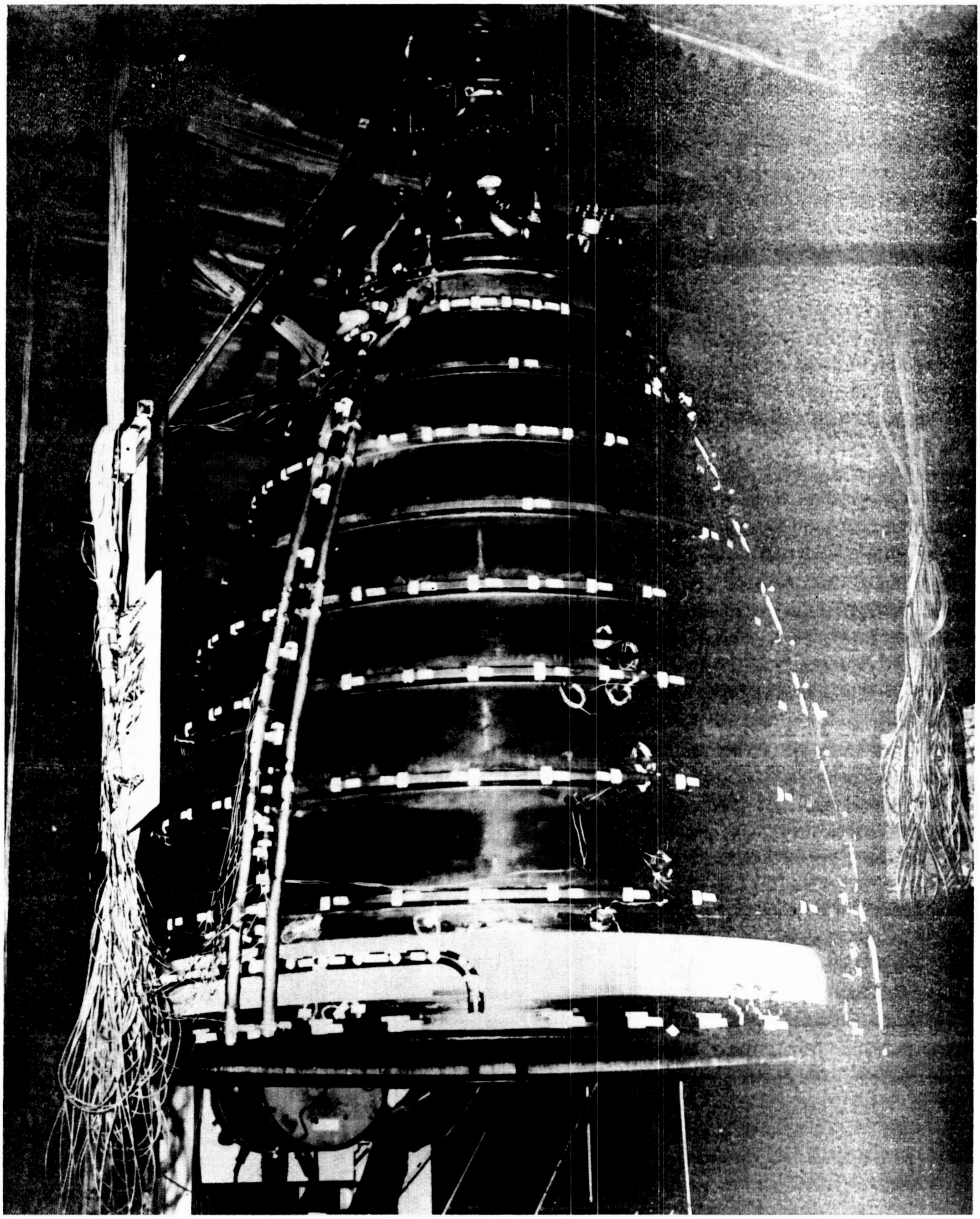


Figure 27. Instrumented nozzle.

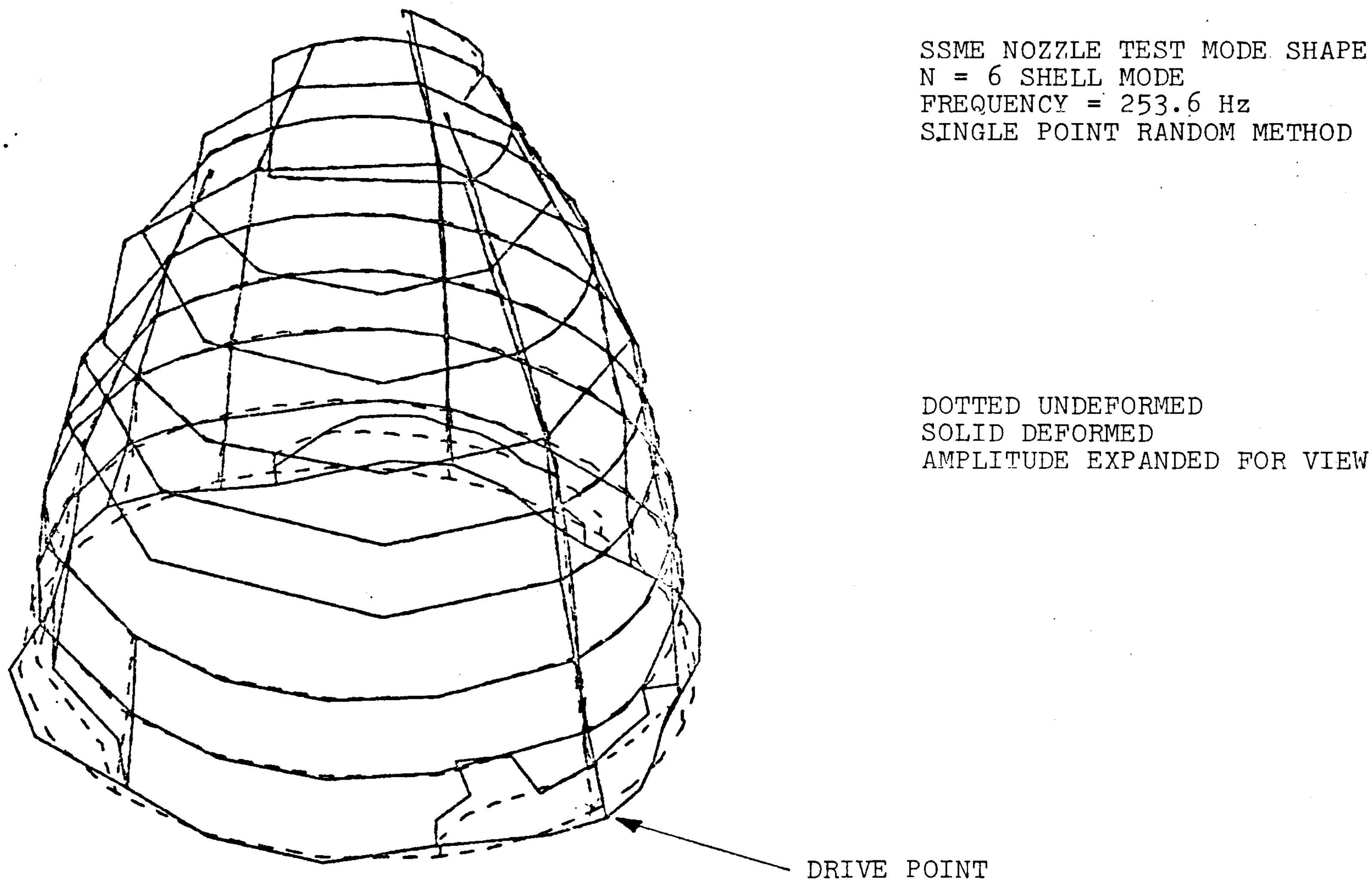


Figure 28. SSME nozzle test mode shape.

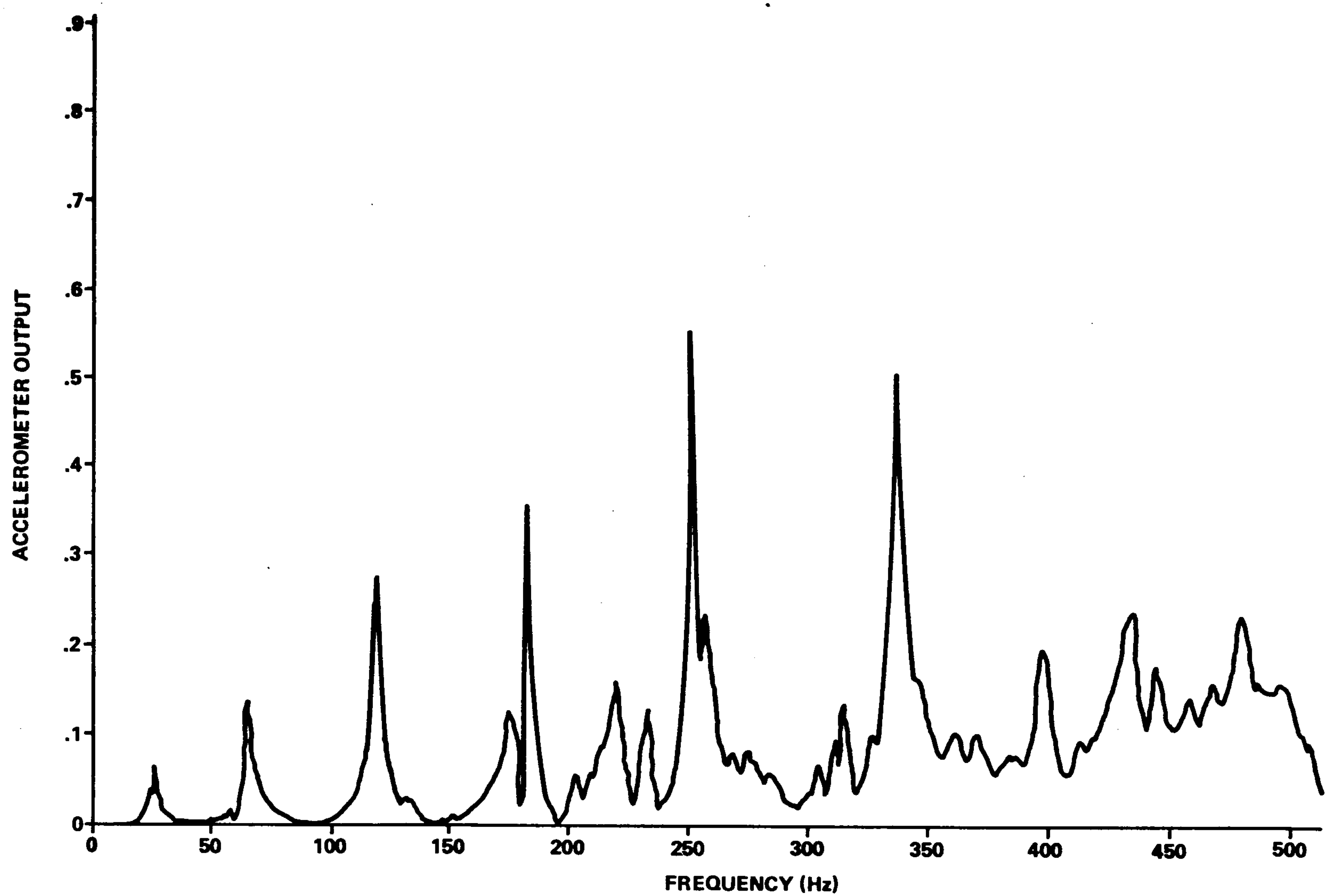


Figure 29. Nozzle frequency response.

The most difficult part of the structure to simulate was the felt-metal pad between the feedline and its mount. This introduced nonlinear stiffness and damping and led to the use of separate low amplitude and high amplitude models.

Good test-analysis correlation was required of the entire frequency range, since (1) the disturbance was wideband, (2) response of modified structure must be calculated, and (3) the operational input was not repeatable. The result of an early test-analysis correlation is shown in Table 7.

TABLE 7. NOZZLE-STEERHORN DYNAMIC TEST RESULTS-ANALYSIS CORRELATION

Description	Test Frequency (Hz)	Damping (%)	Analysis Frequency (Hz)	Difference (%)
N = 2	25.15	0.304	31.02	+23.3
N = 3	65.76	0.177	74.11	+12.7
N = 3, M = 2	120.93	1.165	112.07	-7.9
N = 4	119.04	0.243	123.34	+3.6
N = 5	182.13	0.263	183.73	+0.8
N = 4, M = 2	210.68	0.428	193.44	-8.9
N = 6[a]	253.58	0.261	251.66	-0.8
N = 7	326.77	0.572		
N = 0[a]	338.09	0.646	349.56	+3.4
N = 8	396.55	0.859		
Steerhorn Radial[a]	211.77	1.197	204.22	-3.7

a. Highest gain modes

The single point random test approach proved to be a very efficient tool for verifying the complex set of modes for the engine nozzle steerhorn system.

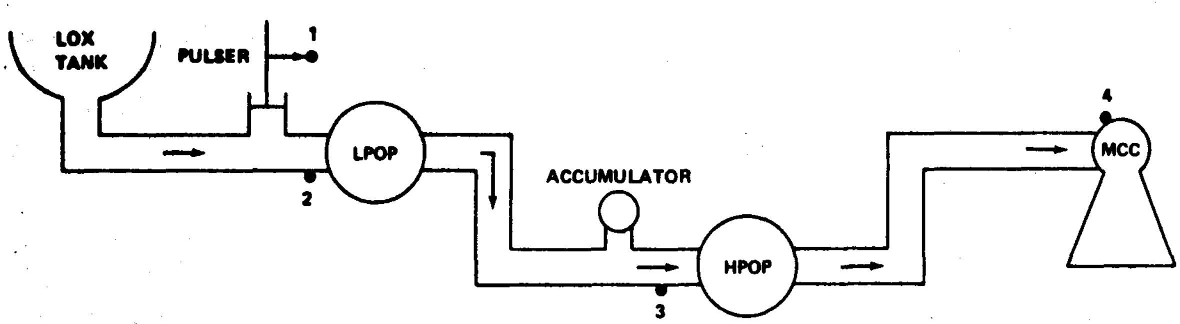
H. Pogo Testing and Analysis

Pressure fluctuation in the lines/ducts of liquid propulsion systems, if allowed to propagate in an unsuppressed manner, will cause pressure oscillations to be observed in the main combustion chamber (MCC) of rocket engines. These pressure oscillations will result in thrust oscillation, which will in turn couple with the structure through the engine thrust support points. This coupling will further aggravate the pressure oscillations, resulting in very large, low frequency, dynamic loads; i.e., pogo oscillations will result which could lead to a catastrophic vehicle failure.

The pogo phenomenon is, in general, a low frequency phenomenon. In the case of the Space Shuttle system, the primary frequency range of interest is from 1 Hz to 50 Hz. As might be expected, this is the frequency range where the majority of the vehicle bending modes are located; therefore, the likelihood of the pressure oscillations coupling with one of these low frequency structural bending modes increases greatly. Consequently, in liquid propulsion systems, accumulators (or suppressors) are implemented in order to attenuate the pressure oscillations which propagate in the lines, ducts, and other elements of these propulsion systems.

Theoretical analysis of the dynamic characteristics (pogo characteristics) of the various elements of liquid propulsion systems is very complex and quite tedious. This analysis can only be verified through full scale dynamic testing of actual engine system hardware. Pogo testing of the Space Shuttle Main Engine (SSME) is currently underway. The primary pogo testing is being performed by Rocketdyne on the single engine test stand at Santa Susana, California. Pogo tests have also been performed on the three engine cluster configuration (MPTA configuration) at NSTL in Mississippi, also by Rocketdyne.

The essential elements of the liquid oxygen (lox) flow system for the SSME are shown in schematic form in Figure 30. This figure also contains the pogo pulsing system currently being used during SSME testing. The lox flows from the lox tank (External Tank) through lines/ducts and valves into the low pressure oxidizer pump (LPOP), past the accumulator into the high pressure oxidizer pump (HPOP), and then to the MCC.



MEASUREMENT	DESCRIPTION
1	PULSER PISTON DISPLACEMENT
2	LPOP INLET PRESSURE
3	HPOP INLET PRESSURE
4	ENGINE CHAMBER PRESSURE

Figure 30. Schematic of SSME pogo pulsing system.

Upstream of the LPOP is a large pulser piston system. Pogo testing is accomplished with the aid of this pulser system. Known pressure oscillations can be injected into the lox flow system and the transfer function characteristics, $H_{xy}(f)$, can be defined (measured) across all essential elements of the lox flow system. Although detailed descriptions of the SSME lox flow system and pogo pulsing system is beyond the scope of the material being presented herein, it can be seen from Figure 26 that all essential characteristics required for pogo stability analysis can be obtained from the system just described. For example, transfer function (both amplitude and phase) can be obtained across each element (LPOP, HPOP, MCC to LPOP) with and without the accumulator for various operating SSME power level conditions and at different suction pressures. As indicated earlier, pogo testing is currently in progress. Table 8 contains a summary of the single engine pogo testing to date. Typical results from these tests will be presented and discussed.

SSME pogo pulsing testing is generally performed in two different modes; i.e., dwell and sweep testing. In the dwell mode, the piston is driven at discrete frequencies for a specified length of time at each frequency. As many as ten different frequencies are tested during a given engine test. In the sweep mode, the pulser piston is swept, in frequency, from 1 Hz to 50 Hz and then down to 1 Hz. This sweeping cycle is continued until several cycles of sweep data are acquired. Typically, during a given test, 40 to 50 seconds of sweep data and approximately 115 seconds of dwell data are acquired.

A general purpose data analysis program was developed by MSFC to provide rapid, efficient, and accurate analysis of the pogo test data. This data reduction and analysis was performed with the HP 5451C Fourier Analyzer System. With the HP 5451C, four data channels can be processed simultaneously. The through-put rate is such that the data (four channels) can be processed (Fourier transformed) in real time with the transformed values being stored on a large disk storage system for further computations.

The software was developed to provide the transfer function characteristics for the HPOP/LPOP, MCC/HPOP, and MCC/LPOP. The transfer function is defined as:

$$H(f) = \frac{\text{Output}}{\text{Input}} = \frac{F_y(f)}{F_x(f)} = \frac{F_{xy}(f)}{F_{xx}(f)} \quad , \tag{1}$$

where

$F_x(f)$ = Fourier spectrum of input

$F_y(f)$ = Fourier spectrum of output

TABLE 8. POGO (PULSE) TESTING STATUS

Test Firing	Configuration	Power Level (%)	NPSP (psig)	Dwell Pulse Time (sec)	Dwell Frequency (Hz)	Remarks
750-061	Accumulator	100	~80	80	3.8, 8.8, 13.8, 18.8, 23.6, 28.6, and 33.6	Bad $HPOP_{in}$
750-062	Accumulator	100	~80	115	3.8, 8.8, 13.8, 18.8, 23.8, 28.6, 33.6, 38.6, 43.6, and 48.6	Bad $HPOP_{in}$
750-063	No Accumulator	100	80.3	100	3.8, 8.8, 13.8, 18.8, 28.6, 33.6, 38.6, and 43.6	All Measurements Good – Strong Coherence
750-064	No Accumulator	100	81.1	100	Same as No. 63	Bad MCC – Other Meas. Good – Strong Coherence
750-066	No Accumulator	100	80.7	110	Same as No. 62	All Meas. Good – Strong Coherence
750-067	No Accumulator	100	32.5	115	Same as No. 62	MCC Bad, Other Meas. Good, Strong Coherence
750-068	No Accumulator	100	81.1	115	Same as No. 62	MCC is Questionable, Other Meas. Good, Strong Coherence
750-069	No Accumulator	100	81.1	115	Same as No. 62	All Meas. Good, Strong Coherence
750-070	No Accumulator	100	~80	115	Same as No. 62	All Meas. Good, Strong Coherence
750-071	No Accumulator	100	32	115	Same as No. 62	All Meas. Good, Strong Coherence
750-073	No Accumulator	70	32	113	Same as No. 62	All Meas. Good, Strong Coherence
750-081	With Accumulator	100	32	115	Same as No. 62	All Meas. Good, Low Coherence < 0.1 for Both Dwells and Sweeps
750-082	With Accumulator	100	32	92	Same as No. 62	

$F_{xy}(f)$ = Cross spectrum - input X output

$F_{xx}(f)$ = Auto spectrum - input.

Also, to provide an indication of the overall quality of the data, the coherence function is computed. The coherence function, γ^2_{xy}, is defined as:

$$\gamma^2_{xy}(f) = \frac{|F_{xy}(f)|^2}{F_{xx}(f)\ F_{yy}(f)} \quad . \tag{2}$$

The broadband fluctuating pressures generated by the lox flow within the lines/ducts tend to become very pronounced at the higher operating power levels. Furthermore, this broadband background noise tends to mask the pulser signals at the higher frequencies and especially with the accumulator in the system. This is particularly true for the sweep tests with the accumulator. In fact, few reliable results have been obtained from the sweep testing either with or without the accumulator because of this very poor signal-to-noise ratio.

In an effort to minimize the effect of this background noise and to improve the signal-to-noise ratio, an additional method of computing the transfer function was performed. This technique used the concept of evaluating the transfer function with respect to a common signal, i.e., pulser, and then forming the ratio of these two transfer functions to arrive at the desired transfer function. The transfer function computed in this manner (ratio method) becomes:

$$H_{xy}(f) = \frac{\{F_{xp}(f)/F_{pp}(f)\}}{\{F_{yp}(f)/F_{pp}(f)\}} \quad . \tag{3}$$

In the case of the transfer function from HPOP/LPOP, equation (3) becomes (Fig. 31):

$$H_{32}(f) = \frac{\{F_{31}(f)/F_{11}(f)\}}{\{F_{21}(f)/F_{11}(f)\}} \quad . \tag{4}$$

The corresponding coherence function (2) (in reciprocal form) is:

$$\gamma^2_{xy}(f) = \left[\frac{1}{\gamma^2_{xp}(f)} + \frac{1}{\gamma^2_{yp}(f)} - 1\right]^{-1} . \tag{5}$$

As indicated earlier, the four channels of information can be acquired (digitized) simultaneously, in real time, with the Fourier transformed values being stored on a "hard" disk. The pogo analysis software program provides the following results:

1) $H_{xy}(f) = |H_{xy}(f)|\ e^{i\theta}$ polar form

where

$|H_{xy}(f)|$ = transfer function gain (both linear and log)

θ = transfer function phase

2) Coherence function, $\gamma^2_{xy}(f)$

3) Power spectral density (PSD) of each measurement

4) Cross power spectral density (CPSD) of each measurement pair

5) A special weighted transfer function in which

a) Only values of the transfer function with a coherence, $\gamma^2_{xy}(f)$, value above a preselected level is retained and plotted, or

b) For dwell data, only values of dwell frequencies are retained and plotted.

The above results are computed in both the ratio technique [equations (3) and (5)], as well as the direct technique [equations (1) and (2)] format for both the sweep and dwell portions of each test. The complete results are computed separately for both the sweep and dwell pulsing durations.

A summary of the typical results of the transfer function, $|H_{xy}(f)|$, obtained from dwell tests without the accumulator using the ratio method for the HPOP/LPOP, MCC/HPOP, and MCC/LPOP is presented in Figures 31, 32, and 33, respectively.

Analysis of test results with the accumulator, as well as detailed comparison of the ratio and direct approaches, is in progress. As indicated earlier, very poor signal-to-noise results when the accumulator is functioning within the lox flow system. This is, in effect, a direct measure of the effectiveness of the accumulator itself. The attenuation of the signal downstream of the accumulator position is so effective that

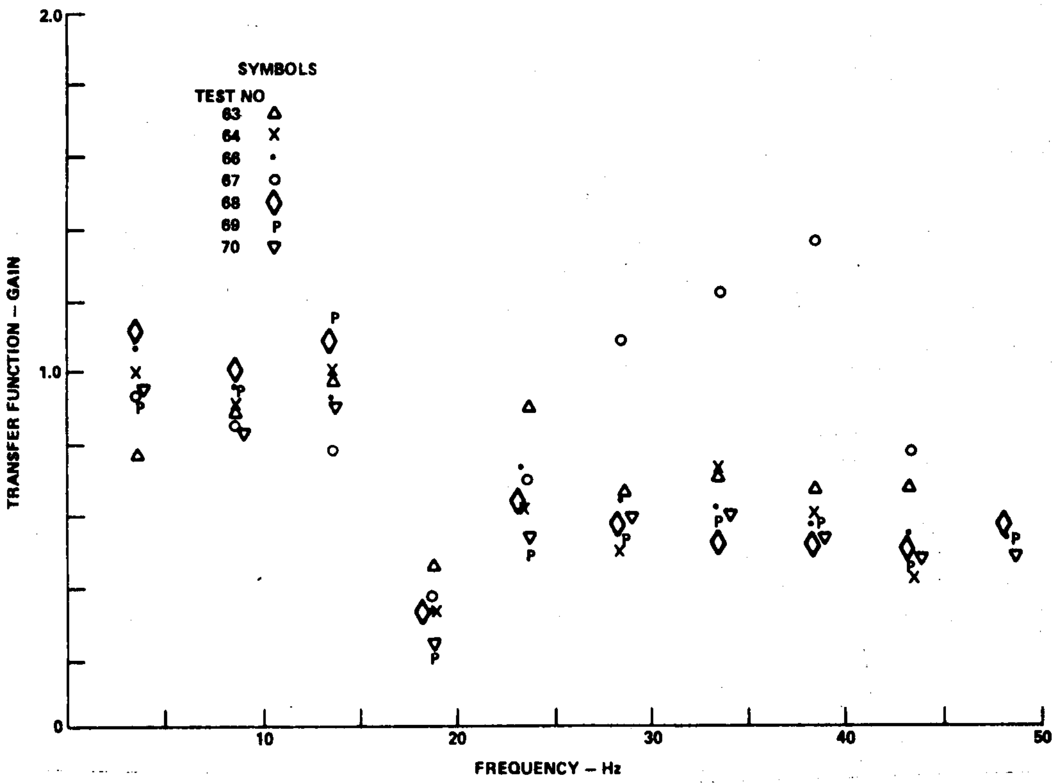


Figure 31. Transfer function gain HPOP/LPOP (ratio method) dwell testing.

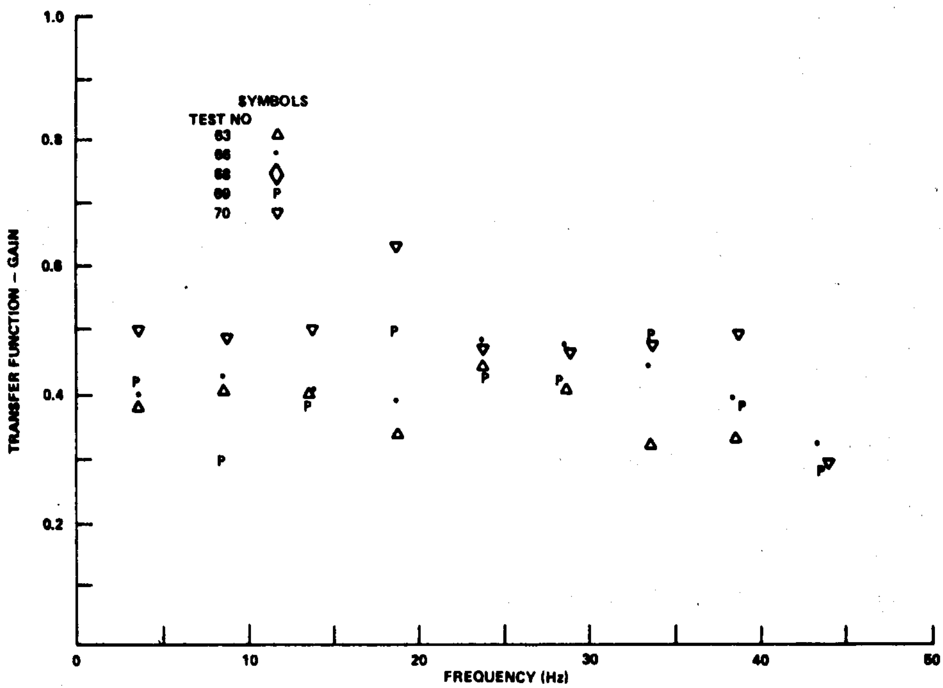


Figure 32. Transfer function gain MCC/HPOP (ratio method) dwell testing.

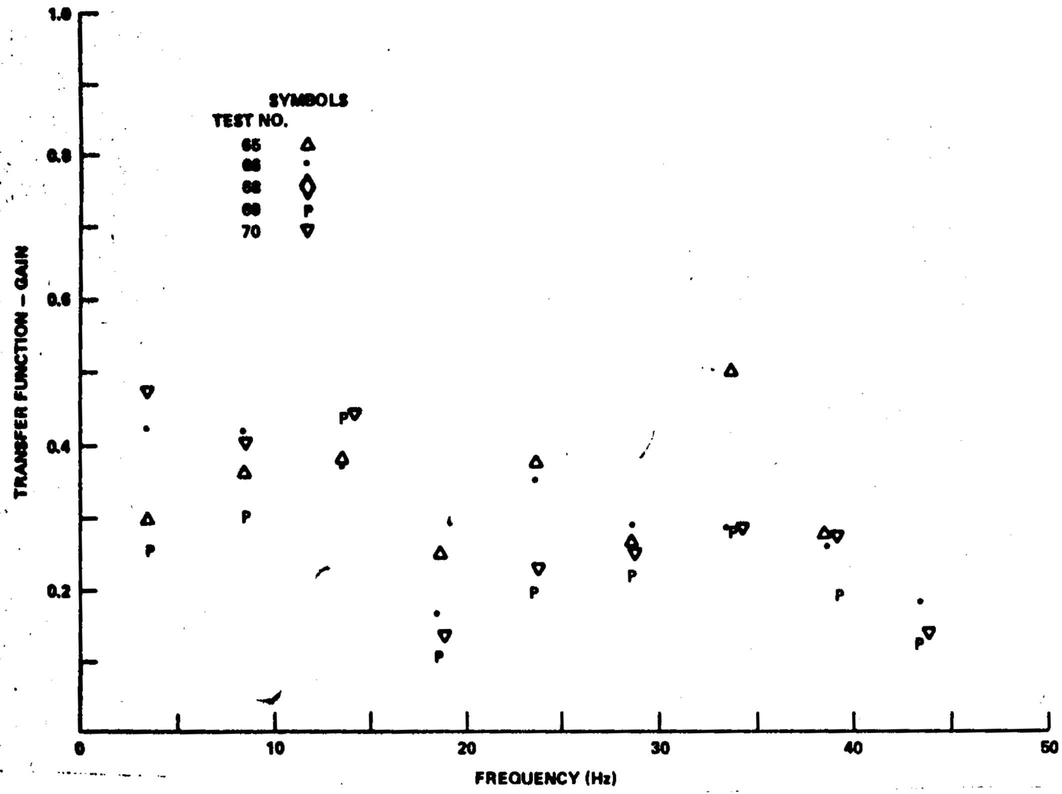


Figure 33. Transfer function gain MCC/LPOP (ratio method) dwell testing.

the signal-to-noise ratio becomes very small, and, consequently, it becomes difficult to provide a reliable estimate of the characteristics of the system (with accumulator) within the constraints imposed by the engine test limitations and schedules.

The measured test results have been compared to the analytical predictions. Typical results for the HPOP/LPOP, for the no accumulator case, are presented in Figure 34.

As can be seen, the comparison between the measured and predicted transfer function is good with the exception of the attenuation of the energy in the 19 Hz region. This attenuation is believed to be due to the duct between the LPOP and HPOP. The analytical pogo model has been modified to account for this loss of energy. Detailed comparison of predicted and measured results, with this dip at 19 Hz, is currently in progress.

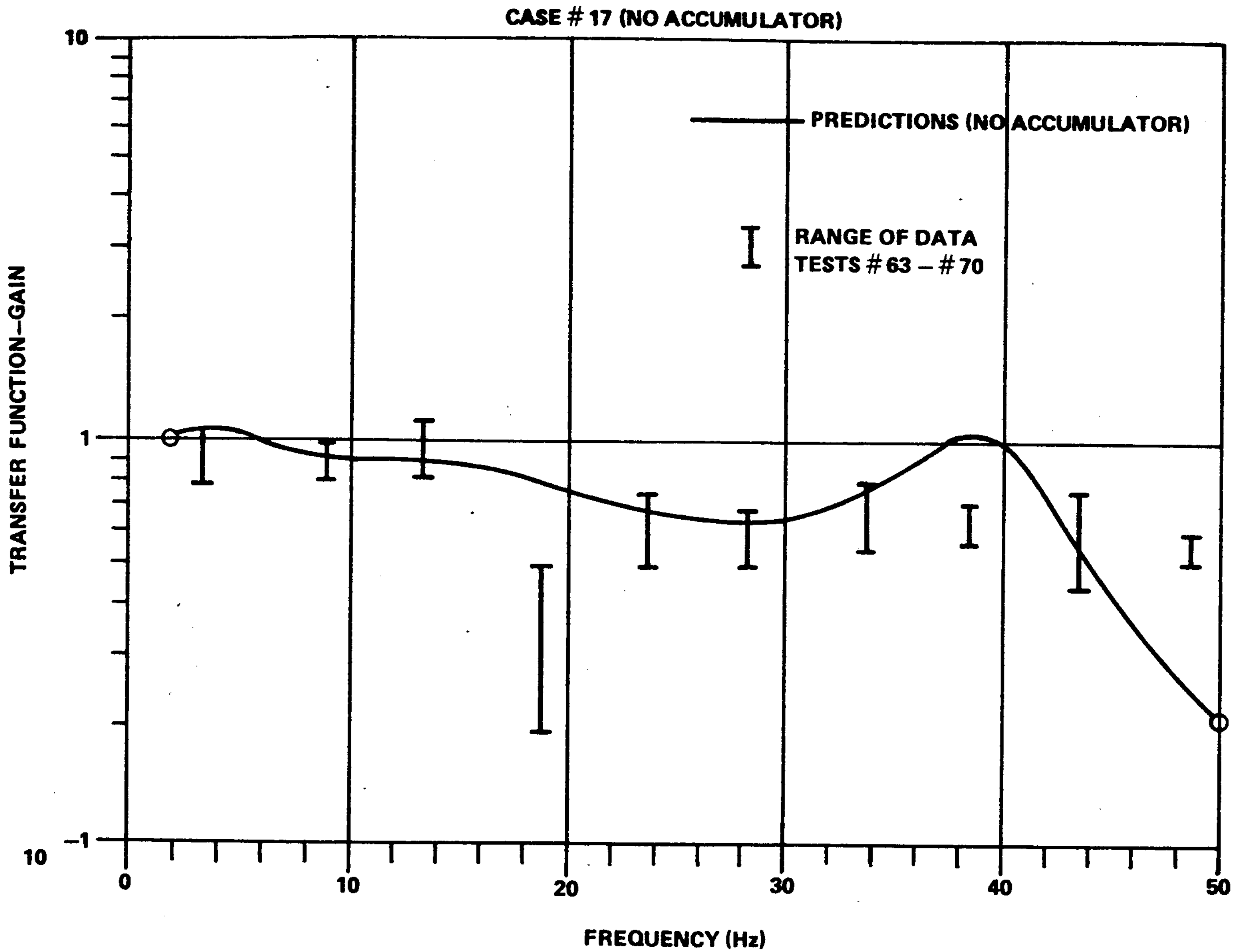


Figure 34. Typical transfer function HPOP/LPOP.

SECTION IV. GENERAL CONCLUSIONS

This section gives an overview of the state-of-the-art testing approaches, their limitations, and technology implications. In a report of this nature, it is not possible to go into detail in each area. Only a top level discussion is given. A reader wanting more detail can find the information the references given or other available literature. The first discussion summarizes lessons learned in dynamic testing, the second deals with state-of-the-art techniques and their limitations, the third summarizes criteria for choosing test and analysis approaches and blends, and the fourth lists potential technology areas.

A. Summary of Lessons Learned

These lessons are based on many years of dynamic testing experience. MSFC has been involved in and conducted several large test programs, such as the Skylab full scale vibroacoustic test, Saturn I and Saturn IB full scale dynamic test, Jupiter full scale test, Shuttle quarter scale and full scale dynamic tests, Space Shuttle Main Engine dynamic test, and Main Propulsion system dynamic test. A brief summary of critical unknowns found in some of these tests is presented in Table 9. The test program, problem discovered, hardware impacted, and consequences if not discovered are identified [19]. Not included are the many minor discrepancies found which allowed for more accurate models and lower launch risks.

The first major lesson that one learns is that engineering must reach a decision as to the purpose of analysis and testing and define dynamic testing prior to test planning. These statements are unique in general, to each project or program [18, 20-27]. The following are examples:

1) The purpose of analysis is to predict the dynamic characteristics to an acceptable accuracy for use in the areas of pogo, control system design, dynamic loads, and aeroelastic analysis, and lifetime verification.

2) The purpose of dynamic testing is twofold: (a) the verification of a baseline mathematical model which will be used for extrapolation to various flight conditions, including payload variations, for use in pogo, loads, control, and flutter design and verification analysis; and (b) to establish a data base for input into analysis and simulations.

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The rest of these summary statements are listed without comment.

1) All analyses and tests are approximations and simulations and cannot duplicate actual flight conditions and configuration.

TABLE 9. DYNAMIC TESTING EXPERIENCE IN PAST PROGRAMS

Test Program	Problems Discovered	Hardware Impacted	Consequences if not Discovered
Saturn V DTV	Local rotation of the flight gyro support plate. Vehicle dynamic shears and moments deformed support plate. The math model under predicted this deformation by 135 percent.	The gyros were relocated to the bottom of the support plate where the local rotation was much less. This required wire harnesses of new length. The flight control filter network was redesigned.	Flight control instability resulting in loss of vehicle.
MARL	Design deficiency in the IU stable platform. Coupling between the stable platform and the ring modes of the IU provided a mechanism for acoustically driving the platform accelerometer against the stops.	Short channel stiffeners were added to AS-501 on the pad. Damping material and a software "reasonableness" test were added later in the program.	Large guidance errors that could cause loss of lunar mission.
Saturn V DTV	Design deficiency in the CSM interface. The single torsional sway brace produced unpredicted high coupling between command module torsional motion and S-IC engine deflection.	Additional torsional sway braces were installed on AS-501 on the pad. Subsequently, the F-1 engines were reorificed to reduce loads at engine cutoff. An engine precant program was implemented to maintain structural integrity in case of engine out.	Structural failure of the CSM interface with loss of vehicle and possible crew loss.
Saturn V DTV	Design deficiency in the SPS tank supports. Unexpectedly high local resonant coupling was detected between SPS tank and bulkhead support.	The upper support bracket for the SPS tanks was redesigned to eliminate a strong tank cantilever mode.	Hardware failure resulting in loss of mission and possible crew loss.
Saturn V	High Lox and fuel dynamic tank bottom pressures. These pressures were under predicted by a factor of 2. The significance of these pressures was not understood until after pogo occurred on AS-502.	The higher tank pressures contributed to the S-IC pogo	Potential loss of vehicle and crew due to pogo.

TABLE 9. (Continued)

Test Program	Problems Discovered	Hardware Impacted	Consequences if not Discovered
Saturn V DTV	High 18 Hz S-IC crossbeam mode gains. DTV data showed that an accumulator should not be used on the inboard engine.	Elimination of a planned inboard engine accumulator.	Potential loss of vehicle and crew due to pogo between an 18 Hz accumulator mode and the 18 Hz crossbeam mode.
Saturn V Short Stack	Strong pitch/longitudinal coupling caused by the lunar module increased the S-IC pogo gain factor by 30 percent. This effect coupled with the tank pressure underprediction was the reason AS-502 pogo was not predicted.	Development and installation of the outboard lox accumulators.	Pogo instability with potential loss of vehicle and crew.
Saturn V Mini A/C	The mechanism triggering S-II pogo was defined. Coupling between the first four lox tank hydroelastic modes when they coalesced with the 16 Hz center engine crossbeam mode produced the pogo instabilities.	An accumulator was developed for the center engine. A back-up cutoff system was also developed. The accurate math model developed during this test supported extensive thrust structure design mods on subsequent vehicles without further testing.	Pogo instability with potential loss of vehicle and crew.
Skylab ATM Test	Strong cross coupling between longitudinal and lateral motions indicated a possible structural failure at S-IC cutoff.	A 1-2-2 engine cutoff hardware and software mod was developed to reduce the longitudinal input to the ATM. Hardware redesigns were laid out in case they were proven necessary by further study.	Hardware failure with potential loss of mission.
Skylab Modal Survey	The strong cross coupling in the ATM proved to be attenuated rather than amplified by the way ATM cross coupling reacted thru vehicle interface.	Test of the total Skylab launch configuration proved the 1-2-2 fix was adequate and that no hardware changes were required.	This test saved a possible redesign of the ATM by verifying structural integrity under the 1-2-2 cutoff.

TABLE 9. (Concluded)

Test Program	Problems Discovered	Hardware Impacted	Consequences if not Discovered
Shuttle MVGVT	SRB mounted rate gyros exhibited abnormally high transfer functions. The rate gyros mounted on the forward SRB ring frames resonated at local frequencies and high gains, which were critical to flight controls.	Structural redesign was required to stiffen SRB ring frame, which revised the local resonant frequencies and reduced the gain.	Flight control inability and possible loss of vehicle.
Shuttle MVGVT	Axial SSME frequencies and mode shapes did not correlate with pretest analysis. A half shell dynamic math model using symmetry was used in the pretest analysis.	A new three-dimensional asymmetric math model of the SSME engines and thrust structure was required. No hardware changes were necessary.	Pogo stability analyses would have been suspect.
Shuttle MVGVT	Test rate gyro values showed greater response variations than analysis. Response variations between RGAs were much larger than those used in the analytical studies in determining the redundancy management (RM) trip levels.	RM software trip levels and cycle counter levels were increased. The fault isolation routine was modified to inhibit kicking out RGAs and ACCs after first sensor failure. (For STS-1 flight only; other flights will be evaluated.)	Flight control instability and possible loss of vehicle.
Shuttle Quarter Scale	Internal SRB pressure effects on stiffness over predicted.	Load impacts with minor redesign of interface backup structure.	Potential failure of interface structure and loss of vehicle.

2) You generally find in testing only what you are looking for or know about.

3) Testing always gives coupled modes influenced by damping. Modal analysis, in general, is uncoupled and undamped.

4) Test plans can only be developed in terms of what is expected. The same is true for facilities, instrumentation, etc.

5) All component or element tests run for use in modal synthesis require great care in instrumentation, amplitude, and phase and constraint definition.

6) Structure and liquid do not scale the same, coupling incorrect.

7) The higher the mode and frequency, the more errors in prediction and testing.

8) Tracing errors or updating large finite element models to match test is very tricky, due to the inability to see the local phenomenon and the large number of parameters available to effect changes.

9) It is only when the user organization requirements are fully understood that the test article can be instrumented and tested properly.

10) Always plan for growth in program objectives.

11) Avoid as much as possible joint replication in scale testing.

12) A major problem in test and analysis is prediction of dynamic tuning of multibody configurations in lightly damped systems.

13) In structures with many joints, actual joint loading is required to take out deadbands, etc.

14) Start test requirements for a systems viewpoint, not a structural dynamics one.

15) Full scale testing comes late in the program at a time when only software or minor structural changes can be made.

16) Criteria must be derived for use in choosing test and analysis approaches and blends.

17) Dynamic testing cannot replace the requirement for good system design practices and analysis approaches. It can only lower the risks associated with these.

18) Communication is a key, close tie between user and tester.

19) Safeguards must be built in to insure no missing important characteristics.

20) Replica models are effective tools to pilot the all-up structural dynamic programs.

21) Understand the limitations of the data reduction routines.

22) Plan every detail of the test and configuration and set up rigid controls.

23) Must design facilities, fixtures, etc., to allow acquisition of wanted characteristics. These design considerations are environments, constraints, material characteristics, scaling, etc.

24) Dynamic test should be firmly based on a comprehensive analytical sensitivity study to define trends and boundaries.

25) Requirements must be reassessed periodically prior to test to remove undue conservatism.

26) Implement a rigid configuration control. Use simulated hardware only where good analytical predictions are possible.

27) Where possible, excite the test article to expected levels to determine nonlinear damping effects.

28) Determine as much information as possible from special test. Do not depend on full scale system test to determine other than interaction effects. For example, determine liquid propellant characteristics in a special slosh test.

29) All test elements, components, associated with dynamic characteristics should be under single point control to insure compatibility.

30) Scale models serve as a contingency for testing anomalies found in flight testing.

B. State-of-the-Art Techniques and Limitations

The use of finite element methods in structures has greatly influenced the trade between analysis and test. Continuous improvements in both flight and ground based microcomputers, in conjunction with parallel processing and new software techniques, have altered tremendously the balance and acceptable test approaches. For example, real-time domain test and flight data analysis procedures provide new tools and insight into the whole area of testing. Although these approaches have added to our analytical ability and enhanced our test approaches, the increased number of degrees of freedom used have greatly increased the problem of updating models to match test results. The overall outcome is a big improvement in our knowledge of structural characteristics. The basic problem with large scale testing, however, is still with us. Large scale verification testing must necessarily occur at a time when most of the structural characteristics have been frozen in detailed design drawings and flight hardware. Consequently, if a problem is uncovered at this point, there is either large cost and schedule impacts or the solution options are narrowed, usually resulting in degraded performance. With this in mind, the discussions that follow will address excitation approaches, data acquisition methods, scale model testing, test hardware and facilities, and general limitations. The bibliography contains a detailed listing of available literature. Individual references will not be singled out in the discussion that follows.

The current state-of-the-art consists of two basic testing techniques; multi-exciter normal mode approach and single excitation source frequency response matrix approach. Time domain analysis is rapidly approaching state-of-the-art status. In the frequency response matrix approach, the modal parameters are estimated from the frequency response using curve fitting techniques. Each of the approaches has advantages and limitations.

1) Normal mode (multi-exciter).

a) Advantages

1. The normal mode is obtained directly from data without curve fitting.

2. Basic modal goodness can be determined while tuning.

3. Accepted technique with broad base usage; understanding of limitations.

b) Disadvantages

1. Requires an extensive excitation system.

2. Difficult to tune in only one mode, especially when modes are closely spaced. Modes are missed.

3. Very slow, time consuming approach requiring prior selection of modes for tuning.

4. Measures only normal modes; complex modes cannot be obtained in this manner.

5. Has potential for missing unknowns not tested for.

6. Burden is placed on testing accuracies.

2) Single exciter frequency response

a) Advantages

1. Measures all modes simultaneously.

2. Data can be kept for future modal analysis if flight test show anomalies.

3. Requires simple exciter control system.

4. Determines complex modes.

5. Very fast, allowing quick return of hardware.

6. Provides insurance against missing unknowns.

b) Disadvantages

1. High modal density systems have accuracy problems in curve fitting for modal data.

2. Normal modes are computationally determined and are, therefore, derived from test data and complex modes.

3. Modal characteristics are a function of exciter position if system has nonlinearities.

4. Burden is placed on computational accuracies and time.

Several approaches are currently under development and show a lot of promise. Use of multiforce source frequency response matrix and time domain analysis are the prime ones. Time domain analysis, to date, is restricted to either free decay or broad random forced response. The advantages and disadvantages are:

1) Advantages

a) Has potential applicability to use in-flight measurements as a means for extracting modal data.

b) Does not require assumptions about the interference of modes due to heavy coupling or large damping.

c) Structure's response is used directly in a computational procedure which yields the vibration parameters.

d) Testing can be done in a series of tests, each covering a frequency spectrum.

e) Fairly insensitive to data noise.

f) Ability to use an overspecified math model to identify number of modes.

g) Structural characteristics can be identified in stages using only two stations at a time.

h) Is less likely to miss modes.

2) Disadvantages

a) Gives a lumped mass system with equivalent frequencies and modal displacements.

b) Has not been demonstrated over a wide range of applications.

c) Modal confidence factor not fully developed.

d) Proven modal acceptance criteria or modal identification criteria not applicable.

e) Cannot evaluate data during test.

f) Force input must be random or response in free decay mode.

g) Hard to eliminate local modes or keep from diluting data.

In the case of multipoint random, the same advantages and disadvantages exist as for the single point, except the exciter position concern and high modal density problems are greatly reduced.

It is clear by this time that no one approach has all the answers. The dynamicist and test engineers must choose based on the individual test objective and hardware.

Regardless of the test approach, one must deal with several other areas. Instrumentation is a key one. Accelerometers are very accurate and are proven. Rate indicators are available also; however, in general, only special control sensor locations are monitored for rates and, in this case, actual control hardware is used. Displacement gauges are available as well as strain gauges. Accuracy is somewhat of a question in these cases, but the characteristics of these instruments are well known and documented. The major problem with this class of instrumentation is the requirement for large, expensive cabling and data collection systems. This is not a major problem on present payloads and transportation system in ground testing; however, this is a major problem for very lightweight structures and testing of large systems in space. The same is true in characterizing internal rotating parts of the pump, etc.

Here techniques using remote sensing are important. Some work has been done and shows potential, but it is still early to give a good evaluation. The need for these remote sensing approaches is very clear but not mandatory.

Excitation systems with their control systems are very key areas. Particularly, these are critical in multishaker modal dwell approaches or approaches that require accurate knowledge of the excitation forces. Controllers and control system software are state-of-the-art. The critical area is the criteria used for determining what constitutes a valid mode for acquisition. Most of these systems used a modal sweep to identify high response frequency regimes. The systems basically work by dwelling at very small frequency increments and changing the blend of various shakers to tunes in the mode. The real and imaginery parts of the responses (quadratunes) are used as criteria for identification of these modes. Various approaches have been developed as criteria. The choice depends on test objectives, hardware characteristics, etc., and is up to the engineers. Since these are state-of-the-art, they will not be discussed further. The major limitations of these approaches are their ability to separate out accurately closely grouped and highly coupled modes. Said another way, drive the mode to modal purity, tuning out influence of other modes. This requires extensive instrumentation and many times post processing to insure this modal purity. Also, it is not always possible to have either the number of shakers or shaker locations required to get the modal purity.

The facilities and the support or suspension systems are the limiting factors many times in the success or failure of a test. The vehicle being tested must be isolated from the facilities or the constraints and boundary conditions defined very accurately, in general, a soft suspension system using mechanical or air springs and/or hydraulic or air support bearings. A factor of 5 on vehicle frequency to support frequency is considered adequate. On systems where the environments are important to the modal characteristics, the facilities and suspension system become very complex or greatly limit the scope of the test. The most difficult of all environments to achieve in ground testing is zero g. For large scale structures, this is basically impossible. This leads to the consideration or requirement for on-orbit testing with very limited means in the instrumentation and excitation areas.

One potential of getting around this requirement (on-orbit testing) is the use of scale model testing. Scale model testing has been used in the past in two ways: (1) early in the program to identify problem areas and get a handle on problem areas and model verification, and (2) device for conducting sensitivity studies and verifying fixes late in the program where full scale hardware and the changes required to effect fixes are too costly and impact schedules. The Shuttle quarter scale model is being held for this kind of activity, particularly for payload interaction testing. In this case, full scale hardware could be released from MVGVT several years early because of the availability of the quarter scale model.

One of the shortcomings of scale model testing is the loading on joints in proportion with the scaling. This means that testing a 1/10 scale model in one g is equivalent to testing a full scale in 1/10 of one g. Carried to the extreme, one could approach zero g in terms of joints by going to higher scale factors. The problem here shifts to manufacturing in that the joint tolerances introduced in manufacturing must be reduced the same factor as the scale factor. Obviously, one cannot afford to build a model like a watch, thus manufacturing skills determine the scale limit. Scale models also have the inherent problem that structural scaling laws and fluid scaling laws have different factors. Where structural fluid coupling is important, this effect is totally missed in scale model testing. Great details must also be given to what subsystems, structural elements, and components can be simulated versus accurate scale modeling. The danger here is that one misses important l effects as was done in the scale model testing of Saturn V. In addi , if one scales down significantly, a specially designed instrumen n and excitation system is required. Recognizing these limitations a aying careful attention to their influences, scale model testing is a le option for many systems and serves as a good supplement, partic early in the program, to full scale testing.

In summary, there are several limit s and/or concerns in testing, which are:

1) Limited to selected modes only (small number, not all modes).

2) Size and cost of full scale test programs are nearing the prohibitive stage.

3) Ability to simulate environment is weak or nonexistent. Testing is valid where the environment is not influential to modal characteristics.

4) Selection of modes in high modal density during testing.

5) Quantifying of constraints and boundary conditions.

6) Scale model manufacturing tolerance requirements.

7) Accurate criteria for modal goodness.

8) Acquiring full scale hardware early enough to impact design.

9) Scaling laws between different systems not the same; eliminating coupling effects in scale modeling.

10) Control of hardware configuration to insure adequacy.

11) Means of insuring unknowns are found.

12) Definition of excitation and other forces required.

The following list is state-of-the-art approaches in the different areas:

1) Excitation
   a) Modal dwells
   b) Slow sweep
   c) Random single and multipoint
   d) Impulsive
   e) Various size shakers
   f) Shaker mixing software.
2) Criteria
   a) Orthogonality
   b) Phase plane/quadratures
   c) Modal confidence.
3) Instrumentation
   a) Accelerometers
   b) Strain gauges
   c) Rate gyros
   d) Displacement gauges.
4) Environment
   a) Drop towers (zero g)
   b) Aircraft (zero g)
   c) Static forces (tension or compression)
   d) Acoustical chambers (small systems).
5) Suspensions
   a) Springs (mechanical)
   b) Air bags
   c) Air bearing
   d) Hydraulic.

C. Criteria for Choosing Analysis and Test Approaches and Blends

It is not possible to formulate a general set of criteria for selecting analysis and test approaches and blends; however, certain guidelines or areas used in developing criteria can be formulated. Some of these are:

1) Mission requirements

   a) Lifetime

   b) Reliability and safety (manned versus unmanned, etc.)

   c) Variability (payloads, mission phases, growths, etc.)

   d) Accuracy requirements (flight mechanics, pointing, etc.)

   e) Maneuvers, etc.

   f) Costs and schedules

   g) Complexity.

2) Configuration characteristics

   a) Joints and interfaces

   b) Type of materials

   c) Static and dynamic coupling

   d) Environments

      1. Thermal
      2. Acoustic
      3. Propulsion
      4. Inertial
      5. Aerodynamic
      6. Pressures

   e) Discipline interaction

      1. Structural/propulsion
      2. Structural/control
      3. Aeroelastic
      4. Hydroelastic
      5. Structural/flight mechanics/control/thermal

   f) Sensitivity of dynamic characteristics to element and subsystem changes.

3) Tools availability

   a) Analysis

   b) Testing

      1. Modal
      2. Element
      3. Full scale.

4) Design requirements

a) Data schedule

b) Hardware availability

c) Accuracies.

5) Organization complexity

a) Number of independent organizations designing various elements

b) Organization location

c) Organization philosophy.

SECTION V. LSS TECHNOLOGY REQUIREMENTS/PLANS

The Space Shuttle test program has been highly successful; therefore, it serves well as a base for future programs. The potential of large systems in space provides the next major opportunity for the application of this experience.

Large space structure (LSS) designs exhibit unique characteristics associated with their structural behavior. Due to their large size and lightweight construction, LSS are low strength, extremely flexible, and have low frequency vibration response characteristics. Inherent in these configurations is a strong coupling between several of the designing disciplines. In particular, the coupling between structural dynamics and control is a key design consideration. The solution to these interactive problems requires efficient and accurate analysis, simulation, test techniques, and properly planned and conducted trade studies. Figure 35 depicts the key issues involved in generic LSS systems [28].

Major issues occur in each discipline as well as between the disciplines. For example, in the integrated dynamics area, key issues involve test and analysis roles and the resulting technologies, testing on the ground for zero g operational systems, and nonlinear analysis approaches. How to model and simulate nonlinearities is a key area as well as whether to design for stiffness requirements structurally or depend on control systems to provide the equivalent stiffness. Other key issues deal with control system approaches, choice of materials, role of man, verification approaches for analytical models, and the role of on-orbit testing, control system logic update, etc., versus all encompassing ground test and development.

Based on these issues a set of key trades result. Figure 36 addresses a partial listing of these trades. There is a major trade between control system complexity and modal data accuracy verification requirements, structural beefup versus using the control system to augment structural damping and stiffness, on-orbit testing and control system update versus ground testing, and distributive control concepts versus structural design concepts.

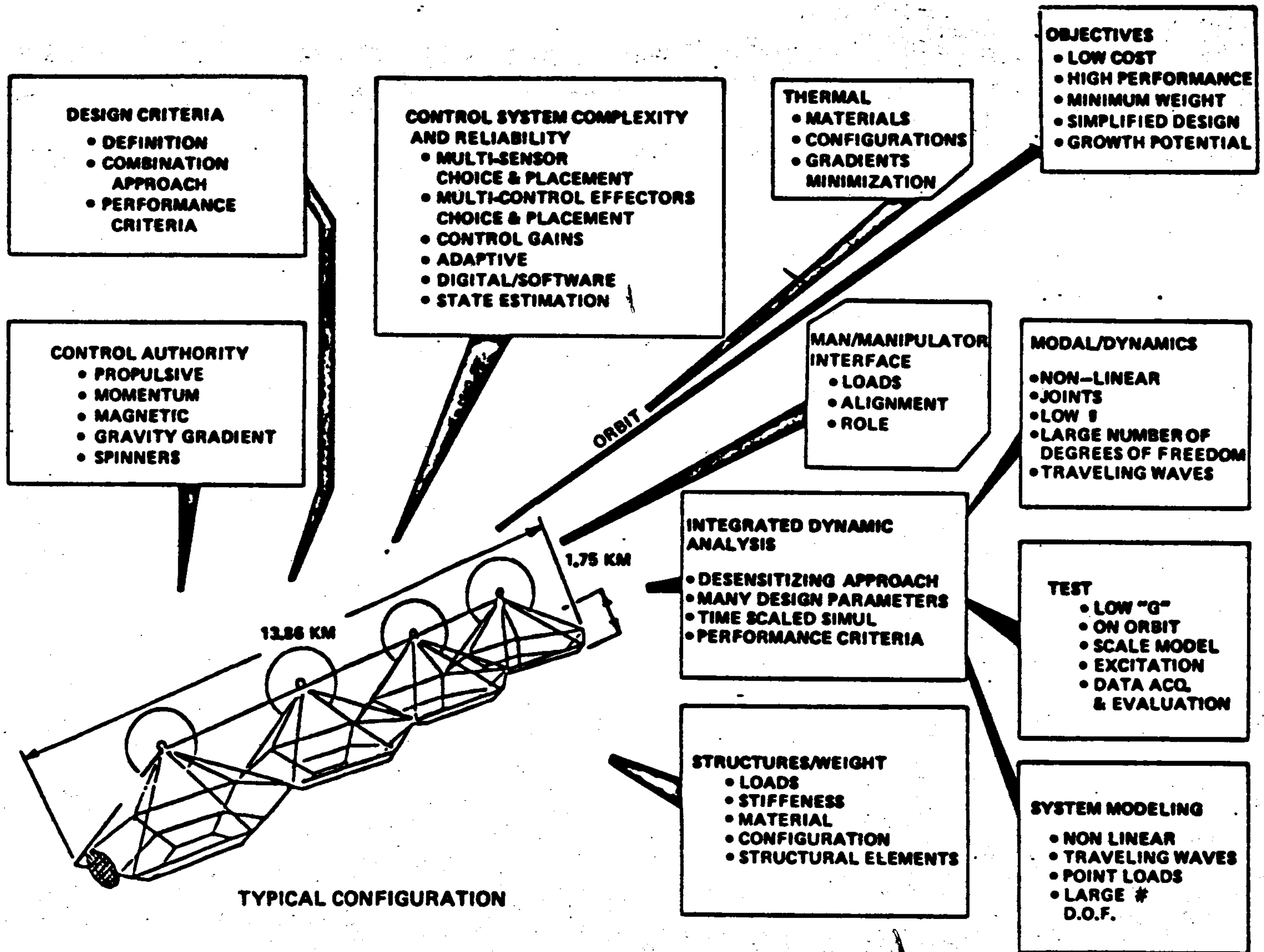
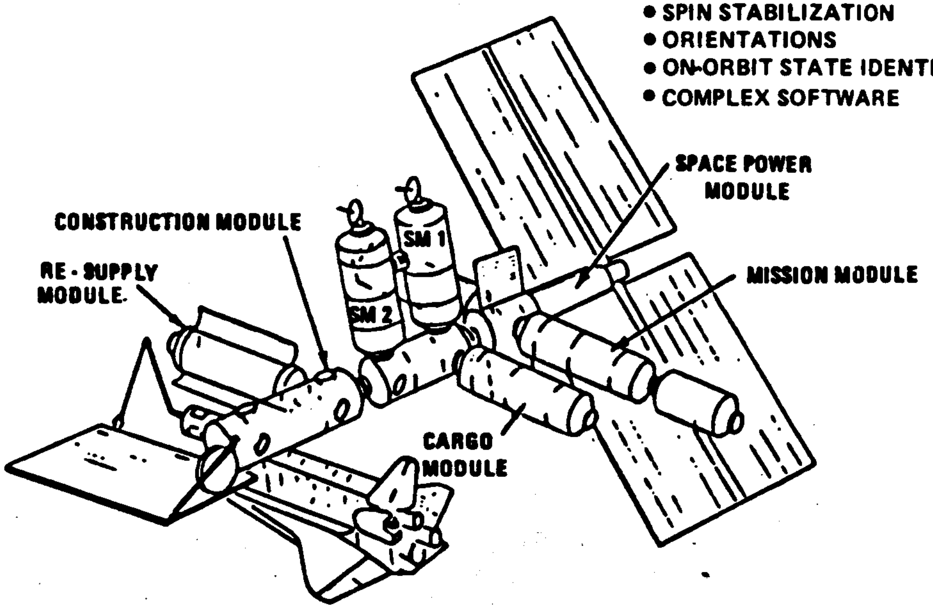


Figure 35. Key LSST issues.

DYNAMIC CHARACTERISTICS
- MULTI-JOINTS/LOAD PATHS
- LOW FREQUENCY HIGH MODAL DENSITY
- LARGE DEFLECTION/NON-LINEAR CHARACTERISTICS
- COMPLEX ANALYSIS AND TEST (ORBIT & GROUND)
- MULTI-CONTROL FORCES/MOMENTS INDUCED LOADS
- STIFFENESS DESIGN REQUIREMENTS

CONTROL COMPLEXITY
- STRUCTURAL CONTROL COUPLING/POINTING AND SHAPE CONTROL REQUIRES COMPLEX SENSOR, FORCE SOURCES
- BLENDING MULTIPLE SENSORS, CONTROL FORCES, DYNAMIC COMPONENTS
- ACCURACY REQUIREMENTS
- ADAPTIVE CONTROL
- SPIN STABILIZATION
- ORIENTATIONS
- ON-ORBIT STATE IDENTIFICATION AND UPDATE
- COMPLEX SOFTWARE

THERMAL CHARACTERISTICS
- MATERIALS
- LOADS



SPACE CONSTRUCTION BASE

Figure 36. Key trade studies.

Additional trades between control, structural geometry (load paths), materials, and thermal are also indicated. Only preliminary assessment of trades for LSS have been made; however, enough information is available to start development of general technology areas and activities in the dynamic analysis and testing regime. Table 10 lists some general project concepts versus dynamic characteristics. It is not possible to lump these characteristics since they vary greatly for one project versus another; however, the high control accuracy requirements coupled with complex geometry is fairly general. Table 11 summarizes these characteristics. Combining these together allows the development of a generalized test program.

TABLE 10. LARGE SPACE STRUCTURES CHARACTERISTICS

Project Characteristics	Science Applications Space Platform	Geosynchronous Space Platform	50 m Precision Shaped Surface Antenna	Solar Power Station
Dimensions (m) Length/Width/Thickness	40/30/1.5	40/30/20	10/50/50	10500/5250/500
Natural Frequency (Hz)	0.6 0.02 Solar Array	1	--	0.0005
Pointing Stability Arc min.	6	1.2	—	3
Topology Form	Tree	Tree	Plate	Plate
Remarks	Baseline No Technology Development Required	No Structural Dynamics or Control Studies in Reports Reviewed.		

TABLE 11. GENERAL CHARACTERISTICS AND CRITERIA

General Characteristics	General Criteria
o Large o Low Stiffness o Light Mass o Controlled o Many Joints o Large Deflections o Growth Accommodation o Distributed and Lumped Damping	o Large o Increase Effective Stiffness o Light Mass o Adaptive or Linear Proportional Control o Active/Passive Structural o Small Deflections (Shape Pointing Control) o Stabilized and Controlled During Growth o Control Damping to Reduce Response

These general characteristics can be broken out into general structural categories: boom and trusses, frame/membrane, shaped surfaces, and platforms. Table 12 shows this breakout in increasing order of complexity along with descriptions and application of each.

TABLE 12. STRUCTURAL DYNAMIC CLASSIFICATION OF LSS

	Type	Description	Flight Application
Increasing Complexity	Booms and Trusses	Long Slender Flexible Structure Sensitive to Joint Characteristics, 0 g Effects, as well as Deployment/Retraction Methods	Masts, Booms
	Frame/Membrane	Large Very Flexible Frame Supported Membranes Sensitive to Coupled Dynamic Motion and Thermal/Vacuum Effects	Solar Arrays and Sails (SEPS SA,...)
	Shaped Surfaces	Large Truss/Frame/Membrane Flexible Structure Whose Shape must be Accurately Known and/or Controlled	Antennas, Lenses, Sun Reflections (Deployable Antenna,...)
	Platform	Very Large Coupled Structural Systems	Stations (GEO platforms)

Figure 37 is the overall flow plan for this generalized plan.

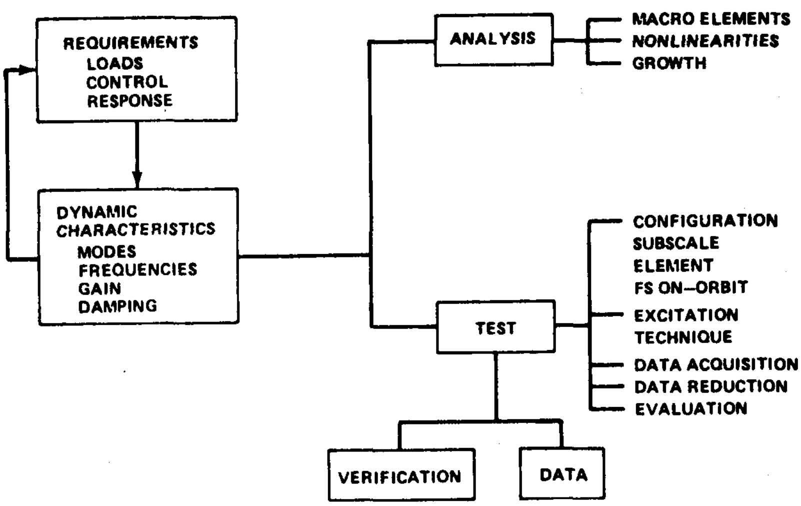


Figure 37. Technology flow plan.

A fundamental part of this plan is the overall system analysis and requirement definition, including structural dynamics sensitivity analysis required to determine basic tests. As a result of these preliminary analyses, basic techniques or approaches evolve. To date, three key areas are apparent: (1) moving from the regime of finite elements to macro-elements or equivalent elements to save cost and computer time, (2) treatment of both geometric and materials nonlinearities, and (3) since most large space systems will not be static but will grow in size and complexity, how to handle growth in analysis is important. Testing technology must parallel these requirements. For example, testing a full system on ground is practically impossible; however, testing of elements on ground is not. One potential ground test approach could conceivably be testing these elements to determine and verify macro-element or equivalent elements for use in large system models in conjunction with scale model system test to verify coupling. Many of the proposed large space systems appear to have the potential for representing major areas with linear models coupled with nonlinear elements. This approach could be verified with a selected coupled element test. Initially, the test program must isolate the problem areas discussed in detail in the section on state-of-the-art and future technology to determine critical areas. Some are obvious if the assumption is made that final system test verification is required. In this case, on-orbit testing is required in order to duplicate the environment, and test the system simultaneously. To achieve this verification, unique remote sensing techniques and sophisticated excitation techniques are required. In addition, it would be highly desirable but not mandatory to have modal/structural dynamic characteristics evaluation or data extraction tools that do not require knowing the forcing function, such as time domain analysis. In addition, model selection and verification criteria that do not require excessive data points to insure data goodness (mode orthogonality, etc.) is mandatory. Only after these techniques have been developed and basic data acquired can the approaches be defined, tools developed, and systems verified in space.

Time-phased flow charts depict current thinking as the approach to use in arriving at these answers. Figure 38 shows the overall interaction with control work, while Figure 39 is the analysis techniques development, and Figure 40 is testing itself. Dates are relative, but are geared to current planning.

Key issues that are apparent in the test and structural dynamics area are:

1) Zero g effects
2) Low natural frequencies with high modal density
3) Joint/interface characteristics
4) Damping (distributed and lumped)
5) Thermal vacuum effects
6) LSS experiment excitation methods

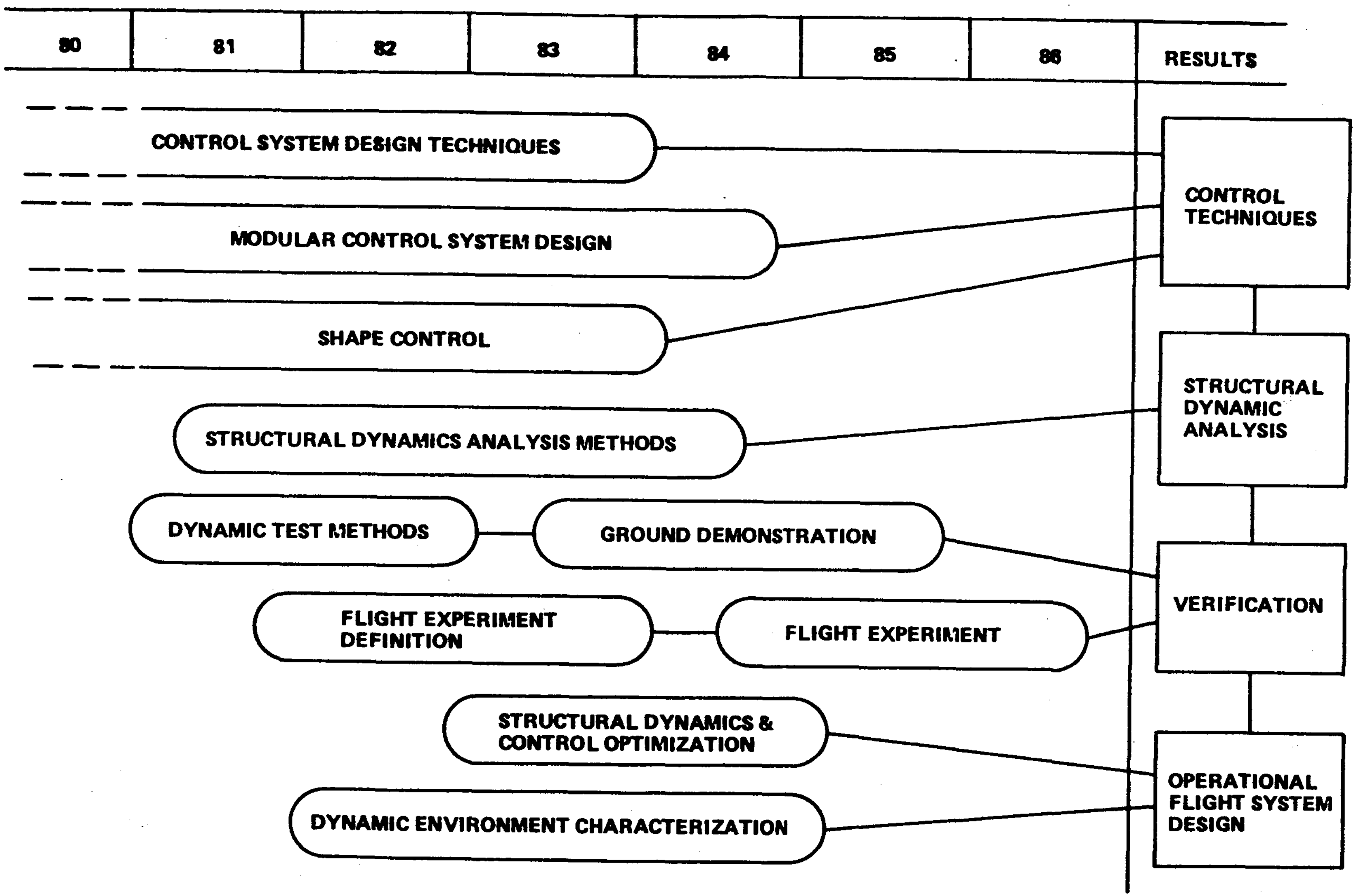


Figure 38. LSS control technology plan.

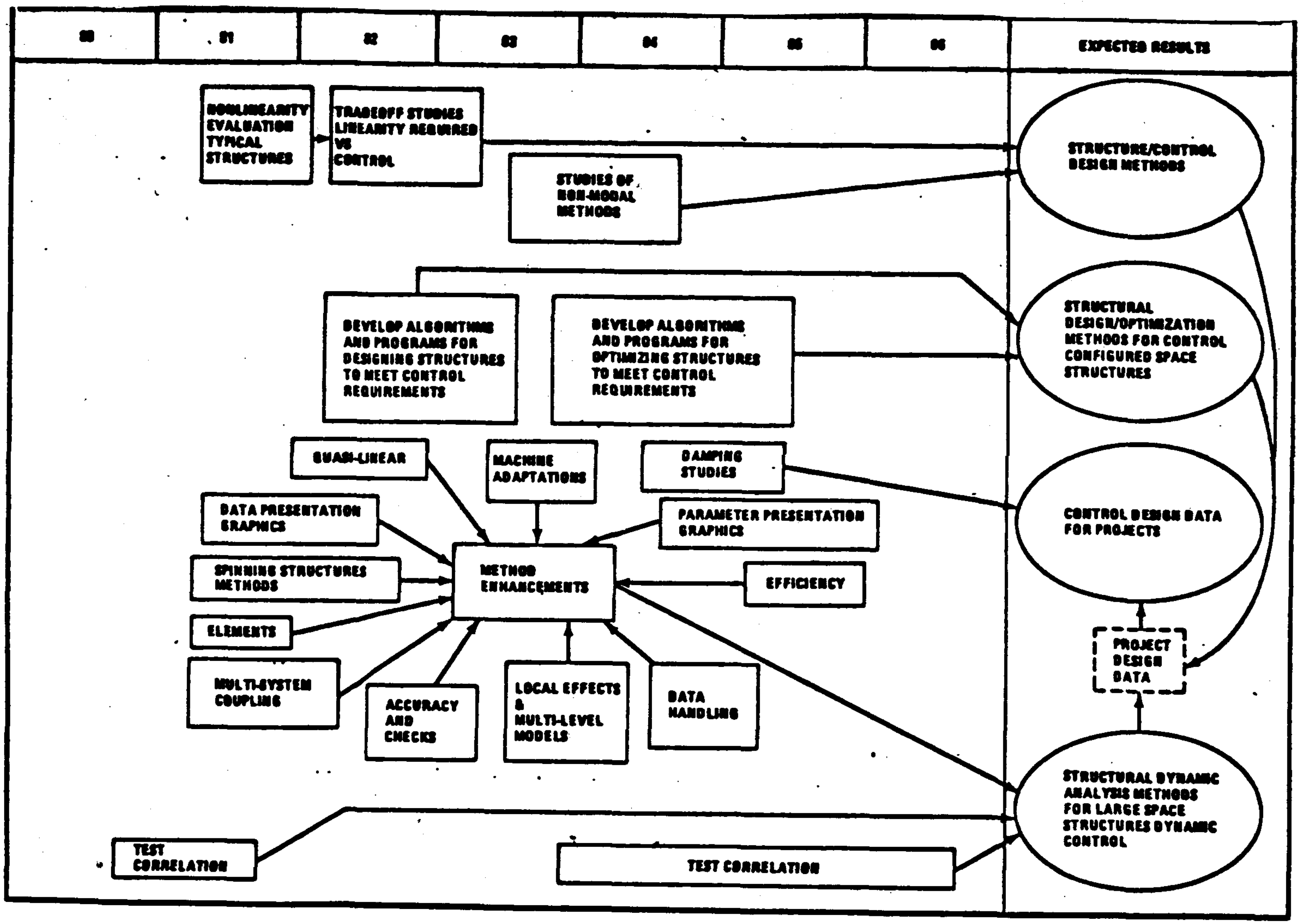


Figure 39. LSS analysis method development plan.

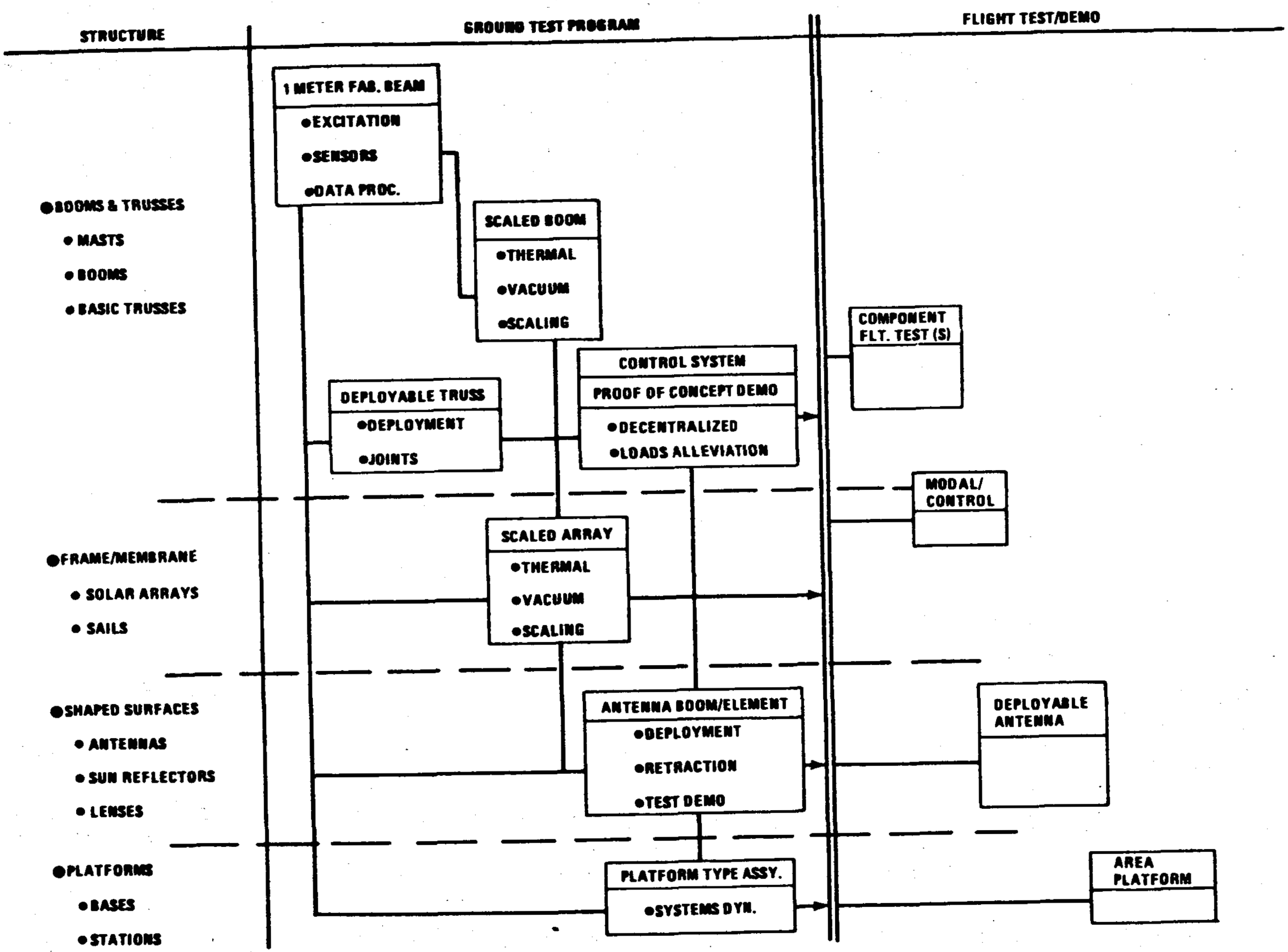


Figure 40. LSS structural dynamic test program.

7) Instrumentation and measurement methods

8) Structural dynamic characteristics

9) Correlation between ground and flat response

10) Sealed structures versus element test

11) Deployment/retraction dynamics.

The plan as given in Figures 38-40 addresses these issues and uses flight test demonstration in conjunction with ground test as a means for resolving these issues. This is to be accomplished by starting with beams, the least complex structure, and moves through to the most complex platforms. Currently, MSFC has built several different lengths of lightweight 1-m beams using the on-orbit beam building machine built by Grumman for NASA. Using a phased test program starting with one beam and building up, it is planned to build the technology base and acquire basic dynamic data. A typical 1-m beam configuration is shown in Figure 41.

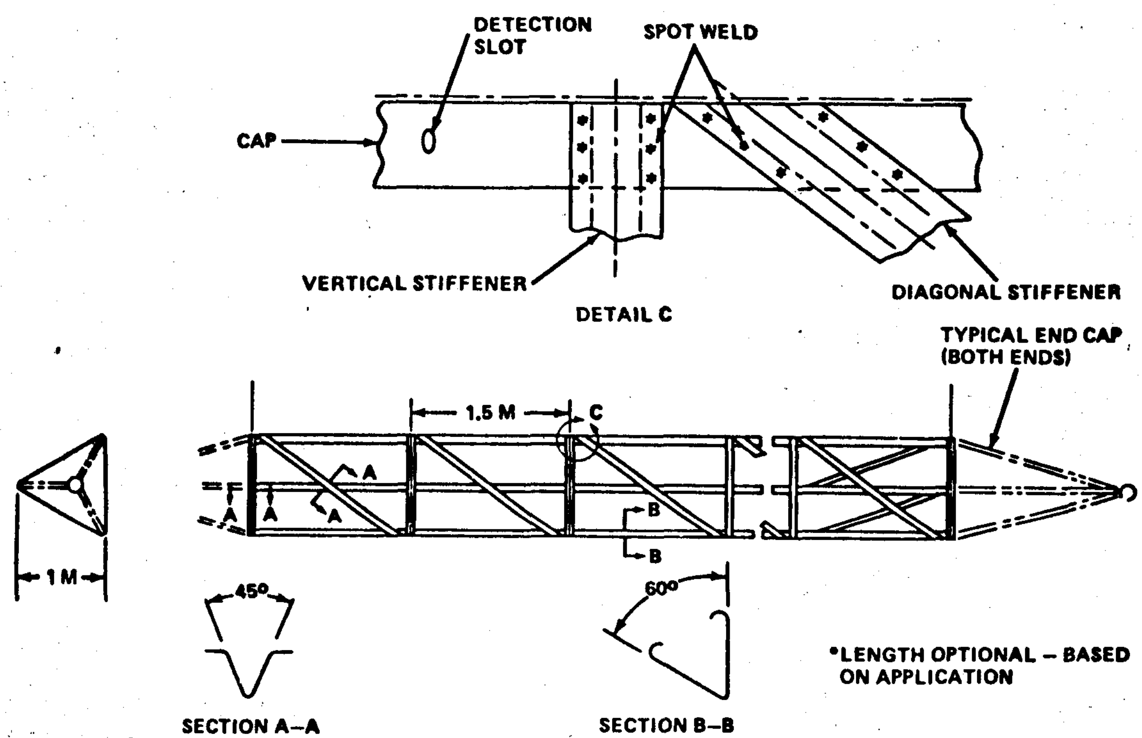


Figure 41. Basic 1-m beam configuration.

In conjunction with this testing, control concepts to handle these characteristics must be developed and verified as well as the final on-orbit verification of the dynamic characteristics. Part of this would be an on-ground demonstration followed by an on-orbit demonstration of the concept using an exemplar experiment. Figure 42 is a type of on-orbit demonstration that could be employed.

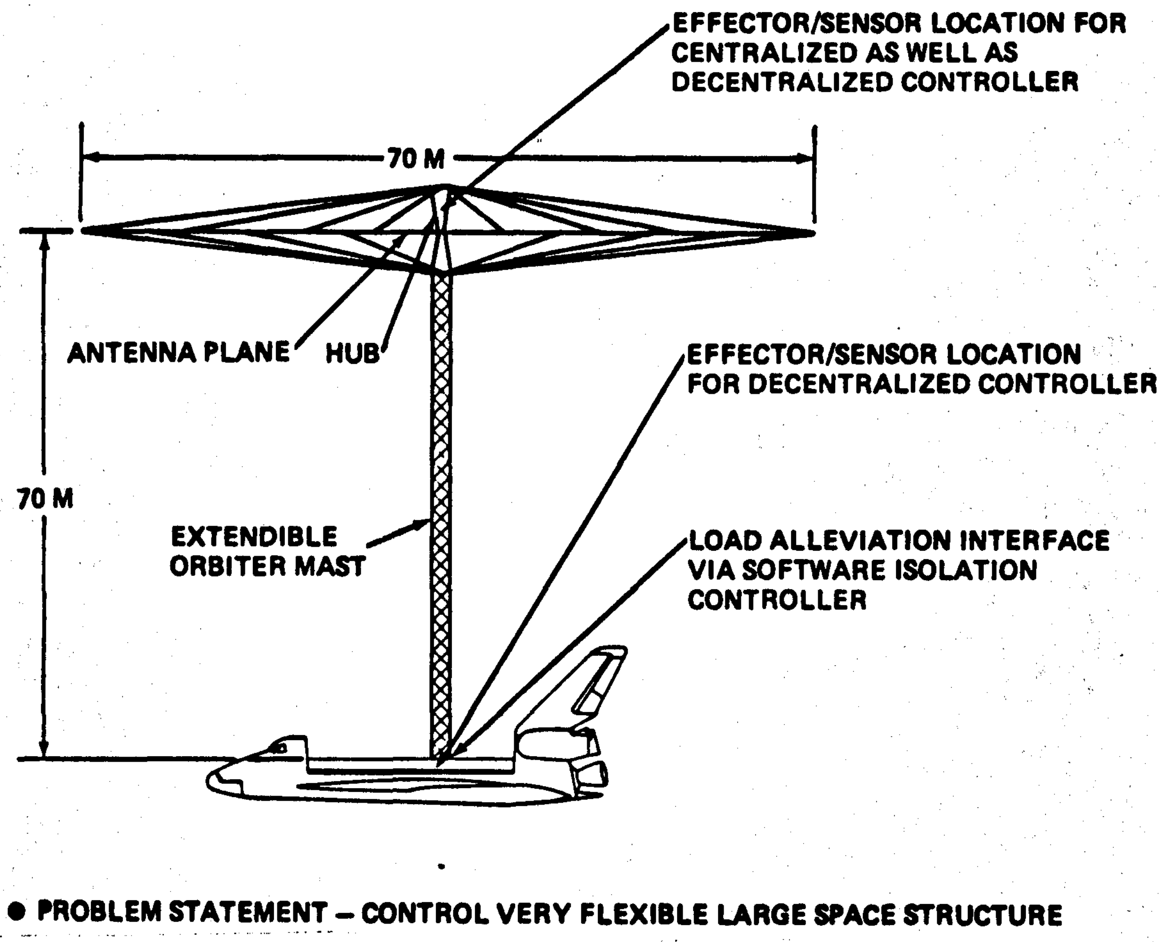


Figure 42. Deployable antenna flight configuration.

Details of the test objectives versus test programs are shown in Figure 43. The key problems stated earlier are addressed in the appropriate test programs. The old problem of excitation methods, measurement techniques, data processing/assessment is key for all. Joints are the next key area. It is clear from this chart that if one must test large space structures, a state identification or dynamic characteristic identifier must be developed that does not require knowledge of the forcing function. In addition, the requirement for many channels or pieces of data to achieve this identification must be drastically reduced. Probably this means that some apriori knowledge of the basic characteristics must be built into the system and that the design is such that minimum cross coupling and dynamic coupling exist. A design requirement might well result which includes isolating elements such as antennas from the basic structure, such as platforms. Section VI discusses state-of-the-art techniques and their limitations and future technology areas.

KEY OBJECTIVE	GROUND TEST PROGRAM							FLIGHT TEST/DEMO			
	1 METER FAB BEAM	DEPLOYABLE TRUSS	SCALED BOOM	SCALED ARRAY	PROOF OF CONCEPT DEMO	ANTENNA BOOM/ELEMENT	PLATFORM TYPE ASSY	COMPONENTS	MODAL/CONTROL	DEPL. ANTENNA	AREA PLATFORM
EXCITATION METHODS	√	√	√	√		√	√	√	√	√	√
MEASUREMENT TECHNIQUES	√	√	√	√	√	√	√	√	√	√	√
DATA PROCESSING/ASSESSMENT	√	√	√	√	√		√		√	√	√
STRUCTURAL DYNAMIC DATA	√	√	√	√	√	√	√	√	√	√	√
JOINTS		√	√	√		√	√		√	√	√
ZERO "G" EFFECTS								√	√	√	√
THERMAL EFFECTS			√	√				√	√	√	√
VACUUM EFFECTS			√	√				√	√	√	√
SCALING			√	√				√	√	√	√
DEPLOYMENT		√				√	√		√	√	
RETRACTION						√	√			√	
CONTROL DYNAMICS									√	√	√

Figure 43. Test objectives versus test programs.

SECTION VI. FUTURE TECHNOLOGY IMPLICATIONS

Technology needs to be advanced in the dynamics area. Obviously, this work splits into two broad areas: analysis techniques and testing techniques. The better the dynamic characteristics can be predicted analytically the less testing required. Since this report is mainly concerned with the test areas, a summary of some of the key technical areas needing attention is as follows:

1) State identification approaches – Present techniques require that one either know accurately the forcing function or eliminate it in order to identify the dynamic characteristics. Development of techniques that will allow identification of the dynamic characteristics without knowledge of the force is very important, particularly for on-orbit testing where elimination of time varying forces, such as gravity gradient and solar pressure, is not possible.

2) Goodness criteria – Closely coupled with state identification modal (dynamic characterization) goodness criteria. Present techniques require many data points and tend to break down when closely grouped

modes increase the impurity of the mode. Techniques that eliminate these shortcomings and consider complex modal characteristics (damping and nonlinearities) are needed. A totally new formulation may be the answer.

3) Sensing – Some work has been done in remote sensing. This is a very fruitful area and approaches being mandatory for on-orbit testing of large space systems.

4) Modal model updating procedures – Although not exactly testing, this is fundamental to the whole procedure and must be improved drastically. How to input test data into models with a large number of degrees of freedom is still an unanswered question. This area must be pursued vigorously.

5) Boundary conditions in substructuring – This is a key area if element testing becomes our basic approach. The key here is the choice of the constraint and the quantification of it.

6) Nonlinearities – How to handle nonlinearities in large systems is essentially unexplored. This is a key area for testing of large, flexible space structures.

7) Sliding connections – A special part of nonlinearities is the problem with sliding connections. Mounting of payloads in the Space Shuttle, large space system in orbit, and many operational payloads have these type connections. How to test and quantify dynamic characteristics under these conditions is a major problem.

8) Prediction of small configuration changes without retesting – In large, highly coupled, multi-element, dynamic systems, the prediction of effects of small changes is difficult. Low damped systems can tune and change characteristics by orders of magnitude with very small changes in hardware. This is a key area to reduce risks and insure success.

9) Environment simulation – This is a crucial area where the environment affects the characteristics. Temperature, static loading of joints, etc., are important. In large structures, these simulations in test are impossible. In small systems, such as rotating machinery and their elements such as turbine blades and impellers, the need is obvious.

10) Model or modal trunction or simplification tools – Present systems contain large numbers of modes and degrees of freedom. Research is needed jointly between test and analysis that will produce verified models that contain essential characteristics but eliminate all others.

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APPROVAL

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By R. Ryan, R. Jewell, F. Bugg, W. Ivey, R. McComas,
L. Kiefling and J. Jones

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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